Analyses of Sea Surface Temperatures in the Northwest Atlantic

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Fisheries and Aquatic Sciences 1410

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ANALYSES OF SEA SURFACE TEMPERATURES IN THE NORTHWEST ATLANTIC

by

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ABSTRACT

Loucks, R.H., and R. W. Trites. 1985. Analyses of sea surface temperatures in the northwest Atlantic. Can. Tech. Rep. Fish. Aquat. Sci. 1410: iv + 42 p.

An investigation of variability of sea surface temperatures for selected areas of the Northwest Atlantic is undertaken, using the "Marine Deck" sea surface temperature (SST) data base. Analyses of SST's include space-time plots of annual anomalies, correlations among monthly anomalies, and computation of empirical orthogonal functions (EOF's) by season. Speculations are offered to interpret the results in terms of wind effects, offshore forcing and river discharge.

RÉSUMÉ

Loucks, R.H., and R. W. Trites. 1985. Analyses of sea surface temperatures in the northwest Atlantic. Can. Tech. Rep. Fish. Aquat. Sci. 1410: iv + 42 p.

Une étude des variations de la température de la surface de la mer en certains endroits du nord-ouest de l'Atlantique est menée au moyen de la base de données sur la température de la surface de la mer (TSM) "Marine Deck". L'analyse des TSM comprend des diagrammes espace-temps des anomalies annuelles, des corrélations entre des anomalies mensuelles et des calculs de fonctions orthogonales empiriques (FOE) par saison. Les résultats sont interprétés en termes d'effets du vent, d'entraînement vers le large et de débits des cours d'eau.

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INTRODUCTION

This report documents many of the analyses performed and the results obtained during a recent contract with Loucks Oceanology Ltd on the subject of variability of sea surface temperature (SST) in the western North Atlantic (north of 30°N and west of 40°W) in the 1940-80 period, utilizing the "Marine Deck" data base. Recently Koslow (1984) found strong empirical orthogonal function (EOF) patterns among Northwest Atlantic fish stocks from the Scotian Shelf to Greenland. Prior to seeking relationships between environmental signals (e.g. SST) and these fish stock patterns, it was decided that the SST's should themselves be analyzed, summarized, and interpreted. This report is a step in this direction.

The "Marine Deck' is the set of weather and sea observations principally collected from cooling water intakes of merchant ships and archived at the National Climatic Center, Asheville, North Carolina. This data base has previously been used by us to calculate monthly SST anomalies by 1° squares and by fishing bank areas in an overview of conditions for the decade of the 1970's (Trites, 1982). Another study (Loucks, 1982), also used the 'Marine Deck' to follow at fortnightly intervals the vernal progression of SST isotherms for purposes of predicting the arrival of mackerel along the inshore area of Nova Scotia. Most recently Trites and Drinkwater (1983) presented a map of SST anomalies that foreshadows the patterns to be identified below.

Several mechanisms may contribute to SST anomalies. Horizontal advection of mean SST by anomalous currents has been found important in studies of SST in the North Pacific (Davis, 1976). Anomalous currents could arise in our area of study both from anomalous winds and from Gulf Stream meanders and rings. The effect of winds on SST anomalies will be addressed. Horizontal advection of SST anomalies by mean currents is anticipated to be important here, especially that due to estuarine circulation originating in the Gulf of St. Lawrence

and in Hudson Bay and extending southward along the Scotian Shelf and Labrador Shelf respectively. In years of strong freshet, the vertical stability is enhanced and positive SST anomalies are observed (Sutcliffe et al., 1976). Anomalous fluxes across the sea surface can lead to SST anomalies. Cloud cover and wind data are available to evaluate this mechanism.

DATA BASE

The 'Marine Deck' observations were obtained for Marsden squares 113-116, 149-152, and 185-187 in the Northwest Atlantic (latitudes 30°N to 60°N and west of 40°W) from the time of earliest observations up to 1981. The individual records in this set have been reformatted to include only atmospheric pressure, air temperature, SST, and cloud cover, as well as time and location. They have been sorted by month, year and SST, checked for duplication, and archived by Fisheries Oceanography Division, Marine Ecology Laboratory, Bedford Institute.

For purposes of analysis, data since 1940 were compiled from these archives for selected areas. The areas, shown in Figure 1, were chosen to include fishing banks where possible and portions of large oceanographic features, such as the Gulf Stream, Labrador current, etc. For each month, 1940 to 1980, the number of observations in a particular area, and the average and standard deviation were computed for atmospheric pressure, air temperature, SST and cloud cover. In addition the median SST was computed. The average and the median are, of course, identical in the case of a Gaussian distribution of SST's. It is the case of the 'contaminated' Gaussian distribution that concerns us - contamination due to erroneous data entries (e.g., reports of SST's exceeding 30°C, which have been found in the 'Marine Deck' data) or due, legitimately to, for example, the occurrence of warm core rings. The median is more resistant than the mean to

being influenced by such 'contamination' while at the same time, the difference, median minus mean, indicates where such contamination exists. The following analyses are based on these monthly (and sometimes three-month) medians; programs from the IMSL package were used (IMSL, 1982).

ANALYSES

A. SST Anomalies

Figure 2 (and Appendix A) shows the annual residuals of SST after extraction of the grand median for the twenty-four areas charted in Figure 1, for the period 1940 to 1980. Notable features are the warm period in the early fifties from the Sargasso Sea to Greenland, and the cool period in the mid-sixties extending as far north as the Labrador Shelf. In addition there is the minor cool period in the mid-seventies extending as far south as the Scotian Shelf and, in the late seventies, another minor cool period occurring south of the Scotian Shelf. The results for the 1970's agree with those of Trites et al. (1985), where normals based on the period 1971 to 1980 were used, in that an apparent node is observed at about latitude 42-43°N (Georges Bank-Gulf of Maine area) separating northern and southern regimes.

B. Correlations between SST anomalies

In the discussion to follow, we distinguish 'between-year' series (e.g. Jan/60, Jan/61, Jan/62....) from 'chronological' series (e.g. Jan/60, Feb/60,. Mar/60....). Davis (1976) uses lagged auto- and cross-correlations between (chronological series) amplitudes of empirical orthogonal function (EOF) modes to demonstrate both persistence and pattern transformations such as might result from advection by permanent currents. Although EOF analyses here (see section C

below) are computed seasonally as 'between-year' series rather than as 'chronological' series, still the first mode winter EOF, for example, shows considerable persistence; the autocorrelation with one-year lag is 0.64; with two years lag, 0.61. Examination of pattern transformations in terms of advection requires a chronological analysis which has not yet been done.

Both Davis (1976) and Haney et al. (1983) relied on the chronological approach; the subject of their studies was the North Pacific Ocean. In the case of the Northwestern Atlantic, it was anticipated that seasonal effects due to winds and river runoff might be quite important, therefore more emphasis has been placed on the seasonal or between-years approach.

The following chronological and between-year correlation analyses, based on observed monthly SST anomalies from discrete areas over 30 years, 1951 to 1980, rather than on spatial patterns (EOF's) were generated in pursuit of evidence for advection along the Scotian Shelf as described by Sutcliffe et al. (1976). As will become apparent, processes in addition to advection play an important role in determining SST. Lauzier (1965) notes that winter SST anomalies dominate annual SST anomalies at St. Andrews, New Brunswick. It is therefore worthwhile to examine correlations with winter SST's to see if these anomalies persist through the year.

1. Autocorrelations (between-years)

Figure 3 shows SST between-years autocorrelations for selected areas. Besides the primary peak for zero lag and small lags of one or two months, there are in all cases secondary peaks at larger lags. In the Eastern Shore and South Shore areas, winter SST anomalies show correlations with those of the following summer. For the Southern New England and Gulf Stream areas, correlations arise for both preceeding and

succeeding seasons. Secondary peaks in subsequent seasons may be interpreted either as reflecting a similar pattern in the primary forcing mechanism or as being due to a secondary, reinforcing influence which arrives only after several months lag. One possible secondary mechanism for the Eastern Shore and South Shore areas is the minimum salinity water exiting the Gulf of St. Lawrence through Cabot Strait in summer. The residue of peak freshet advects into these areas in late summer/autumn, having itself been conditioned by the meteorology of the previous winter through snow accumulation over the drainage basin. It remains to be shown whether or not this freshet reinforces the SST regime established during the winter.

2. Cross-correlations (between-years)

Figure 4 a), b) & c), show space-time plots of SST between years cross-correlations centred on the area, South Shore, for November, January and February. One apparent feature is the spatial coherence over large distances but at small time scales. This is suggestive of direct atmospheric forcing rather than advective linkages. A second feature is the reappearance of secondary peaks lagging by approximately six months and again suggesting the summer reinforcment of winter SST patterns. Thirdly there is the negative result that oblique correlation ridges, which would indicate advection at ocean drift speeds were not discernible. (The underlined entries in Figures 4, 5 and 6 mark areas and lags where the ratio of the cross-correlation to the autocorrelation exhibits a peak. Although these entries show oblique patterns, they occur at lags so large as to imply very slow drifts or delays.)

In overview, the results suggest the importance of direct atmospheric forcing in winter and the possibility of freshet reinforcement over the Scotian Shelf in summer. The opportunity to attempt to reproduce and extend the river discharge versus shore station and lightship temperature results of Stucliffe et al. (1976) using this ocean areas data base is recongized but there is a better chance of freshet advective relationships being detected in a space/time plot of river/SST correlations than in these plots. (In fact Koslow et al. (1985) came very near to addressing just this question.) However, it was decided to confine ourselves here to analyses of the SST data alone. The results of Figure 4 do not provide evidence for advection southwestward from the Scotian Shelf in winter.

3. Cross-correlations (chronological)

Figures 5 and 6 show chronological SST correlations. Again the main feature is the pronounced coherence over large distances at small time scale (zero lag) suggesting atmospheric drivers or some other large scale organizing phenomenon.

C. EOF's calculated from SST anomalies

Empirical orthogonal functions (EOF) analysis (also called principal component analysis) is a technique for summarizing or extracting patterns from data. As an illustration, if a data set consisted of winter average SST's from three sites for ten years, and if these data were plotted on the 3-dimensional scatter diagram, then the first mode EOF (or eigen vector) would be that combination (pattern) of the three sites which defined the major axis of the scatter 'cloud' of data points. The most important axis orthogonal to that major axis would define the combination or pattern of the second mode EOF. A shortcoming of this

technique is that the propagating or time lag aspects of the SST patterns are not revealed, (except by extending the EOF technique to operate on cross-spectral information). To complement EOF analysis, one can examine the lagged correlations for evidence of advection as we have done.

First Mode EOF: Figure 7 (a to d) shows the pattern of the EOF first mode responses or loadings by season for 22 of the 24 areas identified in Figure 1. Two Scotian Shelf areas, Yarmouth and LaHave were omitted. Since the Scotian Shelf was already well represented, the omissions were used as a test for the stability of eigen vectors which showed strong responses on the Scotian Shelf with or without these areas included. The loadings (Figure 7) show considerable uniformity geographically, and between seasons. The loadings almost all have the same sign and their magnitudes often exceed 0.5, signifying that the most important pattern in the data is a relatively uniform increase (or decrease) in SST coherently on a large geographic scale. A chronological EOF analysis, supressing seasonal effects, was also carried out. The resulting patterns were similar.

The first mode accounts for approximately 30% of the total variance in year-to-year seasonal SST anomalies. The region of maximum loadings does shift somewhat with season; from the Scotian Shelf in winter to the Grand Banks in spring to the Scotian Shelf again in summer and to the mid-Atlantic Bight in autumn.

Figure 8 shows the first mode EOF time series formed by convolving the monthly median SST anomalies with the eigen vector loadings. The warm period of the early 1950's and the cool period of the mid 1960's are identified - consistent with Figure 2. As an aside, the spring-time series identifies warm and cool years which is in good agreement with the ranking carried out previously in connection with predicting arrival dates of the 7°C isotherm and hence mackerel along the Nova Scotian coast (Loucks, 1982).

Second Mode EOF: Figure 9 (a to d) shows the eigen vector loadings for the second mode EOF, accounting for approximately 19% of the total variance in seasonal, year-to-year SST anomalies. This mode describes a contrast or negative correlation between temperatures on the Grand Banks and those for the mid-Atlantic Bight. The time-series amplitudes of the second mode EOF are shown in Figure 10. To illustrate, the relatively extreme values for the winters of 1950 and 1970 reflect the fact that there were strong geographic contrasts in SST anomalies; SST's were very warm in the mid-Atlantic Bight and very cool on the Grand Banks in 1950 and just the opposite in 1970.

It is important to note that, whereas sometimes higher modes are to some extent artifacts of the orthogonality constraint, here the contrast or tilt mode is directly interpretable because the correlations between SST's on the Grand Banks and the mid-Atlantic Bight are actually negative.

Modes for EOF Taken Together: In order to look for geograpic similarities and differences in response patterns for the 22 areas, plots of Mode I against Mode II for each of the four seasons are shown in Figure 11. For visual clarity some of the areas have been further grouped together as follows: An Eastern Group (ILC, OLC, CGB, WGB); a Central Group (GSL, SP, ESS, SI), and a Southwestern Group (SS, BR, GOM, GB). A number of points should be noted: the three grouped areas, although displaying seasonal shifts, tend not to vary widely in their position relative to one another, although the Southwestern and Central Groups display appreciable overlap in autumn and winter; the Central Group has predominantly a Mode I loading which is nearly constant at all seasons, whereas the other two Groups show marked seasonal shifts, with the Eastern Group loading primarily on Mode II in autumn while the Southwestern Group loads almost entirely on Mode I during the same season. The Cape Farewell area (CFR) has both low and variable Mode I and II

loadings at all seasons and is distinctly separated at all times from all other areas; the Gulf Stream area (GS) on the other hand has relatively high Mode II loadings in winter and spring and is positioned closely to the Southwestern Group in autumn and winter; the Western Slope Water area (WSL) is closely associated with the Southwestern Group at all times of the year; the Southern New England (SNE) and Mid Atlantic Bight (MAB) areas although closely positioned to each other and in the general area of the plot occupied by the Southwestern Group nevertheless are distinctly separated from it in Winter, Spring, and Summer, the seasons when this pair exhibit high Mode II loading; the Flemish Cap (FC) area is embedded within the Eastern Group in autumn and winter, but is well separated from it in spring and summer; and the Sargasso Sea (SA) and the Gulf Stream (GS) areas are closely grouped in spring and summer, but are widely separated in autumn and winter.

The close graphical position of the Gulf Stream area to the Southwestern Group in autumn and winter suggests at least their association and possibly cause and effect i.e., that the Gulf Stream may well constitute a significant driver for the region southward from the southwestern Scotian Shelf.

The third and fourth modes are not shown; they have not been examined in detail but tend to involve single areas (e.g. Cape Farewell). The first four modes taken together account for some 70% of the variance in the SST field.

SPECULATIONS

In this section the characteristics of some likely forcing mechanisms will be summarized and related to the SST patterns - quite speculatively.

The between-year means and variances of geostrophic winds by season are illustrated in Figure 12. In contrast to SST EOF patterns, these wind variances show marked seasonality at all locations, but especially in the north. Wind

variance is largest in winter and smallest in summer i.e., winter winds may vary widely from year to year while summer winds are much more consistent. Consequently, in the search for mechanisms which might give rise to the year-to-year variations in SST EOG amplitudes, winter winds were examined extensively.

The wind direction of maximum correlation between winds and SST EOF patterns and the percentage variance 'explained' by this particular wind component are given in Table 1. The significant result is that winter and spring winds directed on/offshore bear the strongest relation to SST's and account for approximately 30 to 50% of the between-year variance in the first mode EOF time series.

To turn to some characteristics of the river runoff impinging on the Scotian Shelf, Figure 13 suggests a relationship between the annual anomaly of St. Lawrence rivers discharge (i.e., RIVSUM: Sutcliffe et al. 1976) and winter geostrophic winds (northward component) over the Scotian Shelf.

The scale of weather patterns is such that one might reasonably expect anomalous winds on the Scotian Shelf to be associated with anomalous precipitation patterns over the St. Lawrence drainage basin, and in turn to affect subsequent freshwater discharge from the river. The anomalies appear to interact constructively. Northward (i.e. onshore) anomaly winds are associated with higher winter SST's (Table 1) and with positive runoff anomalies (Figure 13); the latter have been shown by Sutcliffe et al. (1976) to be associated with positive SST anomalies in summer and autumn. The notion that river runoff and offshore forcing have common cause (in winter meteorology) is supported by Figure 14. Winter temperatures from the Western Slope Water region, with 7-year normally weighted smoothing, show close correspondence with the smoothed series of St. Lawrence River discharges from the previous spring. This surprising relation suggests an answer to the puzzling observation (Sutcliffe et al., 1976) that although

sea surface temperature anomalies are coherent and advectively linked down the Atlantic seaboard, yet positive temperature anomalies are associated with salinity minima on the Scotian Shelf and salinity maxima off New England. If perturbations in the discharge from Gulf of St. Lawrence Rivers and in temperatures of the Gulf Stream have common parentage in large-scale atmospheric variability and if, where they meet in the vicinity of the Gulf of Maine area, the temperature anomalies are of the same sign, albeit arising via different circumstances, then the large-scale, persistent coherence of SST anomalies follows.

SUMMARY

(1) SST's show persistance from season to season (Figs 8 & 10), particularly from winter to summer (Figs. 3 & 4), and from year to year (Fig. 2).

(2) SST's are coherent over large geographical scale (Figs. 2, 4, 5, 6, & 7).

(3) Stimulated by the observations that (a) winter winds are strong and most variable interannually (Fig. 12), (b) that river runoff is related to winter winds (Fig. 13), (c) that runoff is known to be related to SST on the Scotian Shelf, presumably because it increases the vertical stability of the water column, and (d) that winter SST's and those of the succeeding summer are correlated (Figs. 3 & 4), the following scenario is suggested. Strong (weak) runoff provides a pathway for reinforcing and prolonging the warm (cool) imprint of winter winds upon summer SST's over the Scotian Shelf (St. Lawrence rivers) and the Grand Banks (Hudson Bay rivers), thus the winter winds establish an anomaly pattern of large geographical scale and this pattern is sustained over time through reinforcement via a river pathway.

(4) Georges Bank, and South New England area SST's are also strongly influenced by winter winds (Table 2). These SST's are correlated with those

of preceeding as well as succeeding summers (Fig. 3), perhaps reflecting the influence of the Gulf Stream (Figs 3 & 11).

(5) The large-scale first EOF mode appears to be supported by winds in winter and spring (Table 1), and by river and offshore influences in summer and autumn (Figs. 7 & 11). The smaller-scale second mode remains a puzzle; it may be associated with the Slope Water/Gulf Stream system (Fig. 11), but winds also appear to play a role (Table 1).

(6) Our overview impression is that winter meteorology 'sets the scene' for SST's; that there is a direct influence of winds on winter SST's through anomalous advection and surface fluxes, and two indirect pathways -one through precipitation over the continent and subsequent river runoff and coastwise drift, and the other through perturbation, by anomalous winds and wind curl, of the North Atlantic gyre. This latter pathway is the more hypothetical; nevertheless there is some supportive evidence i.e., Fig. 14.

It seems that the winter meteorological signal proceeds along the three pathways simultaneously such that the signal via the direct path impinges on SST's immediately (winter/spring) and the signal via the two indirect pathways impinges (and reinforces) later (summer/autumn/winter).

Finally, it appears that the river influence and the offshore influence intersect in the Gulf of Maine area in autumn/winter 'in phase' with respect to SST and 'out of phase' with respect to salinity.

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Figure Captions

Figure 1. Chart showing the areas over which SST observations have been averaged monthly.

Figure 2. Space-time plot of annual SST anomalies over the period 1940-80. Stippled areas depict positive anomalies.

Figure 3. Between-year autocorrelations for four particular areas lagged and leading the months November to March.

Figure 4a. Space-time plot of between-year cross-correlations centred on South Shore, November, 9 equivalent degrees of freedom, $r \geq 0.59$ significant at the 95% level. Underlined entries designate cross-correlation 'peaks' relative to the autocorrelation for the same lag.

Figure 4b. As in Figure 4a but for January, 7 equivalent degrees of freedom, $r \geq 0.68$ significant at the 95% level.

Figure 4c. As in Figure 4a but for February, 7 equivalent degrees of freedom, $r \geq 0.68$ significant at the 95% level.

Figure 5. Space-time plot of chronological cross-correlations based on Eastern Shore, 155 equivalent degrees of freedom, $r \geq 0.13$ significant at the 95% level. Underlined entries designate cross-correlation 'peaks' relative to the autocorrelation for the same lag.

Figure 6. As for Figure 5, but based on South Shore, 124 equivalent degrees of freedom, $r \geq 0.15$ significant at the 95% level. Underlined entries designate cross-correlation 'peaks' relative to the autocorrelation for the same lag.

Figure 7a. Charts showing the eigenvector loadings for the first mode EOF's of SST for Winter (Jan-Mar).

Figure 7b. Charts showing the eigenvector loadings for the first mode EOF's of SST for Spring (Apr-Jun).

Figure 7c. Charts showing the eigenvector loadings for the first mode EOF's of SST for Summer (Jul-Sep).

Figure 7d. Charts showing the eigenvector loadings for the first mode EOF's of SST for Autumn (Oct-Dec).

Figure 8 Amplitudes of the first mode EOF's of SST by season. Peaks reflect warm years and troughs, cool years.

Figure 9a. Charts showing the eigenvector loadings for the second mode EOF's of SST for Winter (Jan-Mar).

Figure 9b. Charts showing the eigenvector loadings for the second mode EOF's of SST for Spring (Apr-June).

Figure 9c. Charts showing the eigenvector loadings for the second mode EOF's of SST for Summer (Jul-Sep).

Figure 9d. Charts showing the eigenvector loadings for the second mode EOF's of SST for Autumn (Oct-Dec).

Figure 10. Amplitudes of second mode EOF's by season. Peaks reflect positive anomalies in the New England region and negative anomalies in the Grand Banks region.

Figure 11. Plot of first vs second mode EOF loadings of SST for all twenty-two ocean areas showing natural groupings.

Figure 12. Seasonal average geostrophic wind vectors together with between-year variance components for five locations on the continental shelf (Thompson and Hazen, 1983). The orientation of the adjacent shore is also shown.

Figure 13. Scatter diagram of the northward component of Scotian Shelf geostrophic winds (in winter) (Thompson and Hazen, 1983) and anomaly of annual discharge of the St. Lawrence Rivers (RIVSUM; Sutcliffe et al., 1976) in that year.

Figure 14. Time plot of spring discharge of St. Lawrence Rivers (averaged over April, May and June and (7-point binomial filter), and the subsequent winter western Slope Water (WSL) surface temperature (averaged over January, February and March and similarly smoothed).

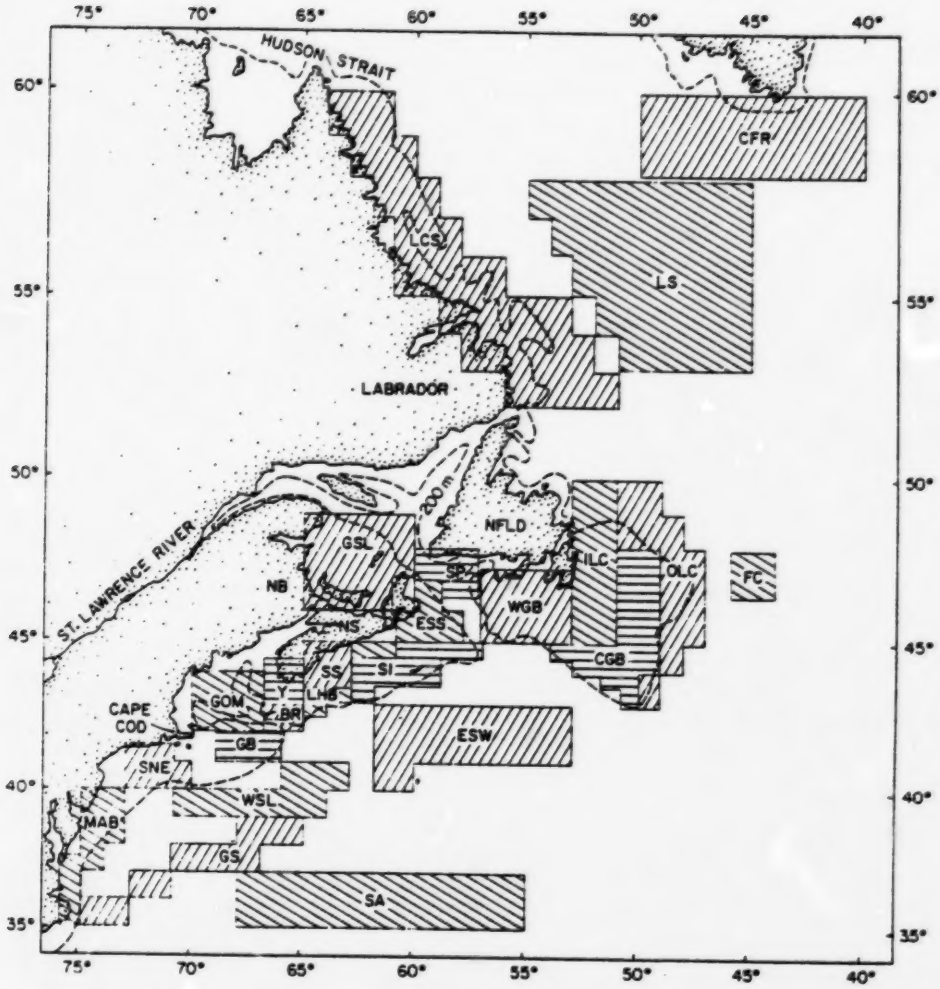

Figure 1. Chart showing the areas over which SST observations have been averaged monthly.

Figure 2. Space-time plot of annual SST anomalies over the period 1940-80. Stippled areas depict positive anomalies.

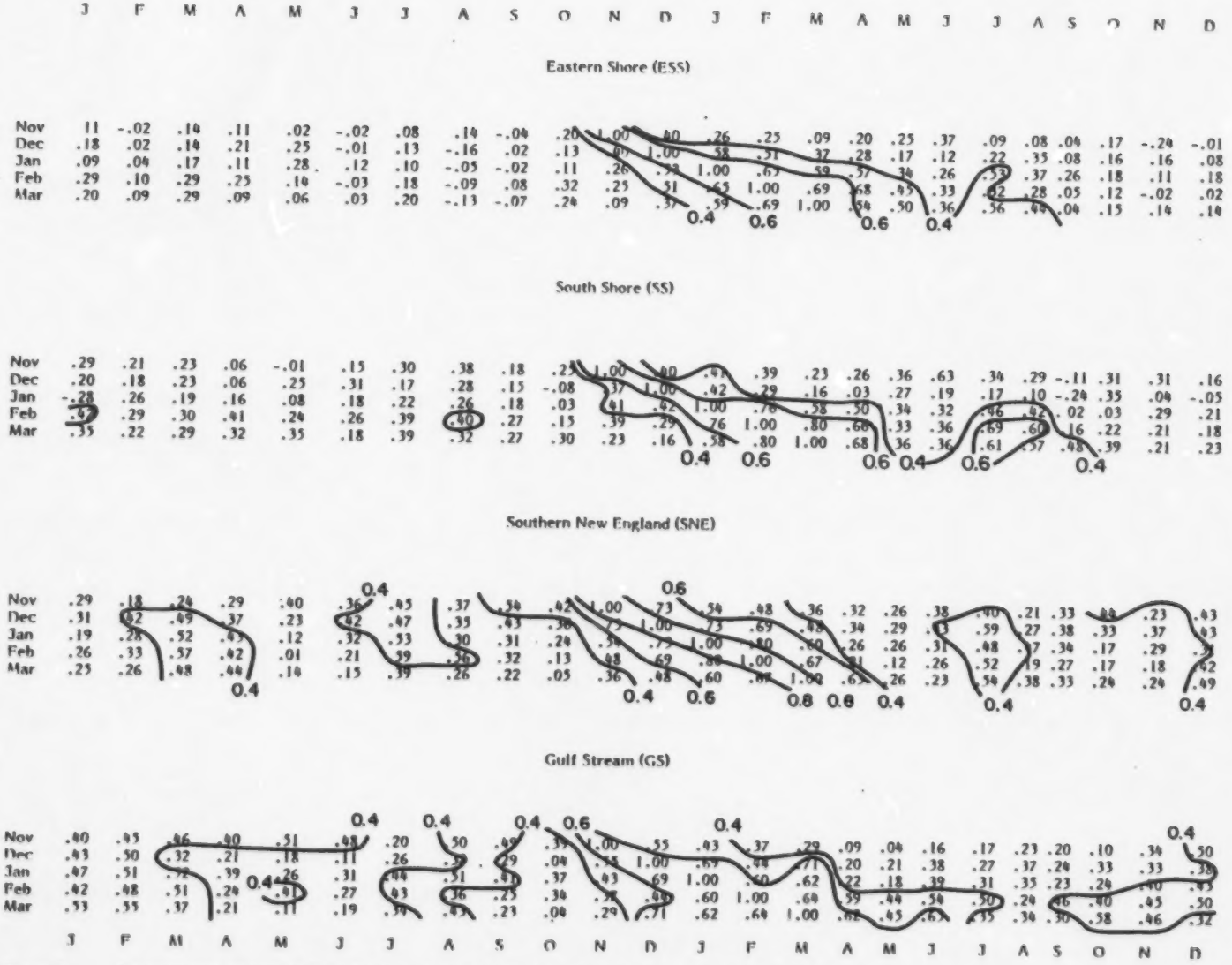

Figure 3. Between-year autocorrelations for four particular areas lagged and leading the months November to March.

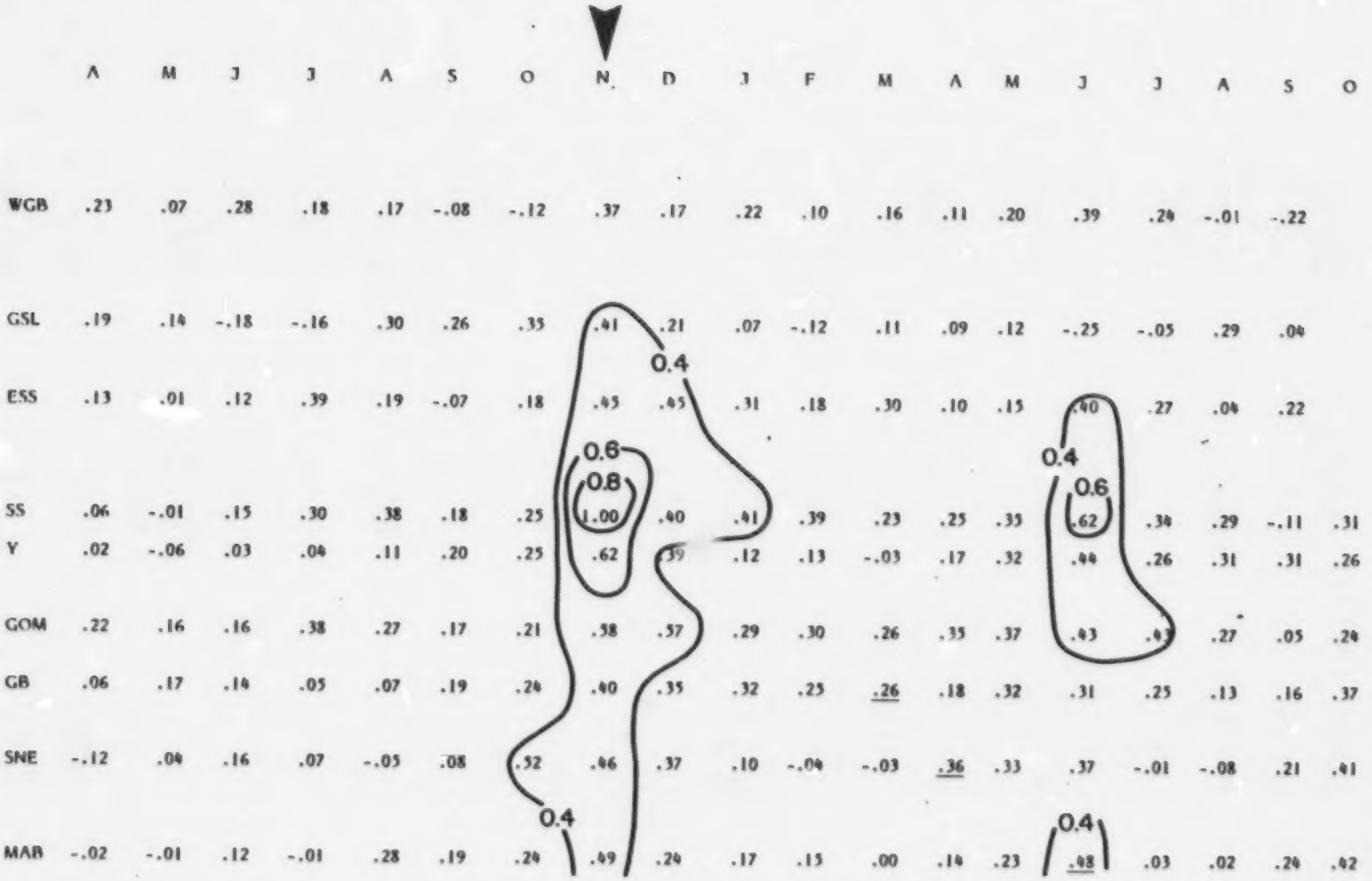

Figure 4a. Space-time plot of between-year cross-correlations centred on South Shore, November, 9 equivalent degrees of freedom, r≥0.39 significant at the 95% level.
Underlined entries designate cross-correlation 'peaks' relative to the autocorrelation for the same lag.

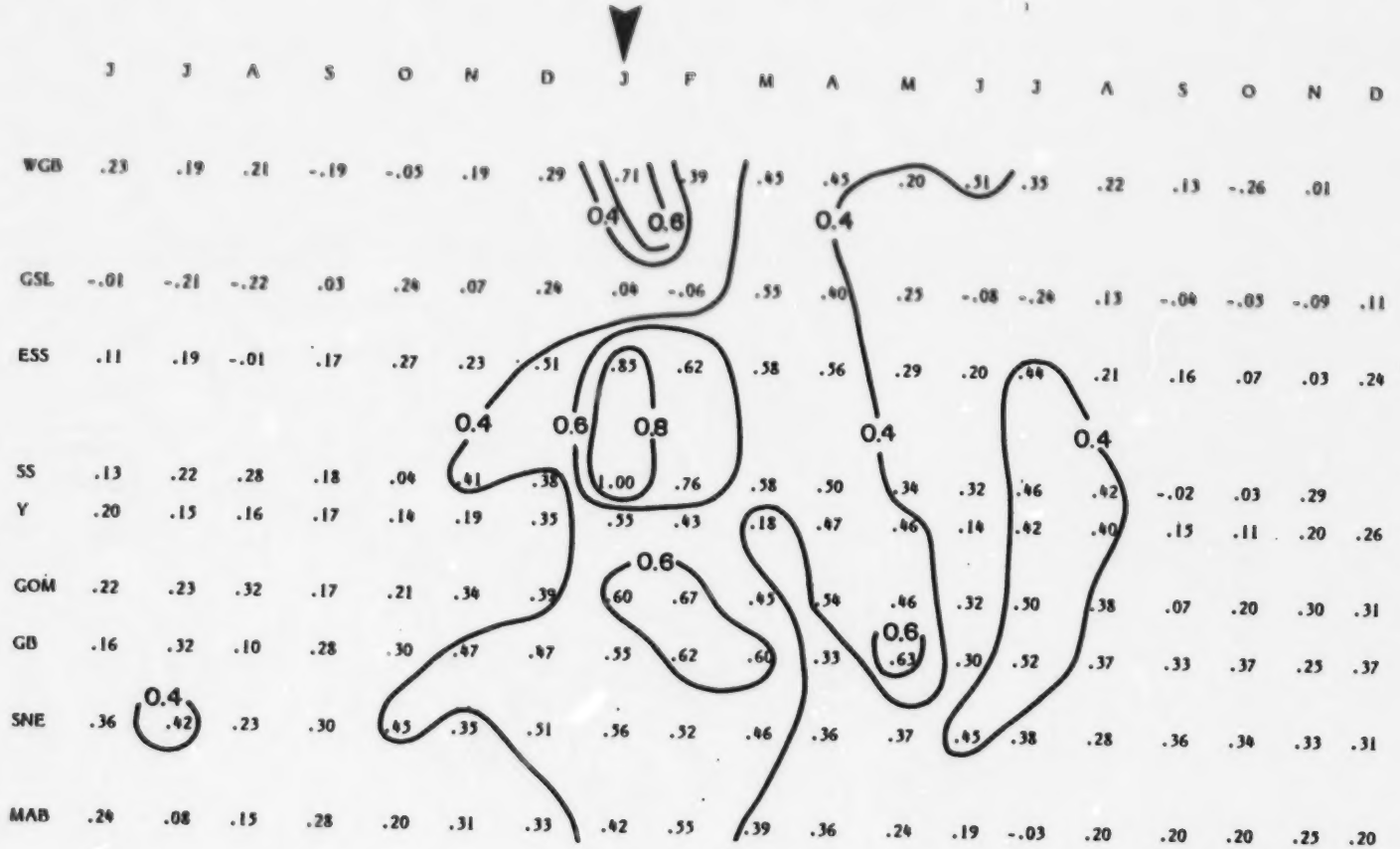

Figure 4b. As in Figure 4a) but for January, 7 equivalent degrees of freedom, $r \geq 0.68$ significant at the 95% level. Underlined entries designate corss-correlation 'peaks' relative to the autocorrelation for the same lag.

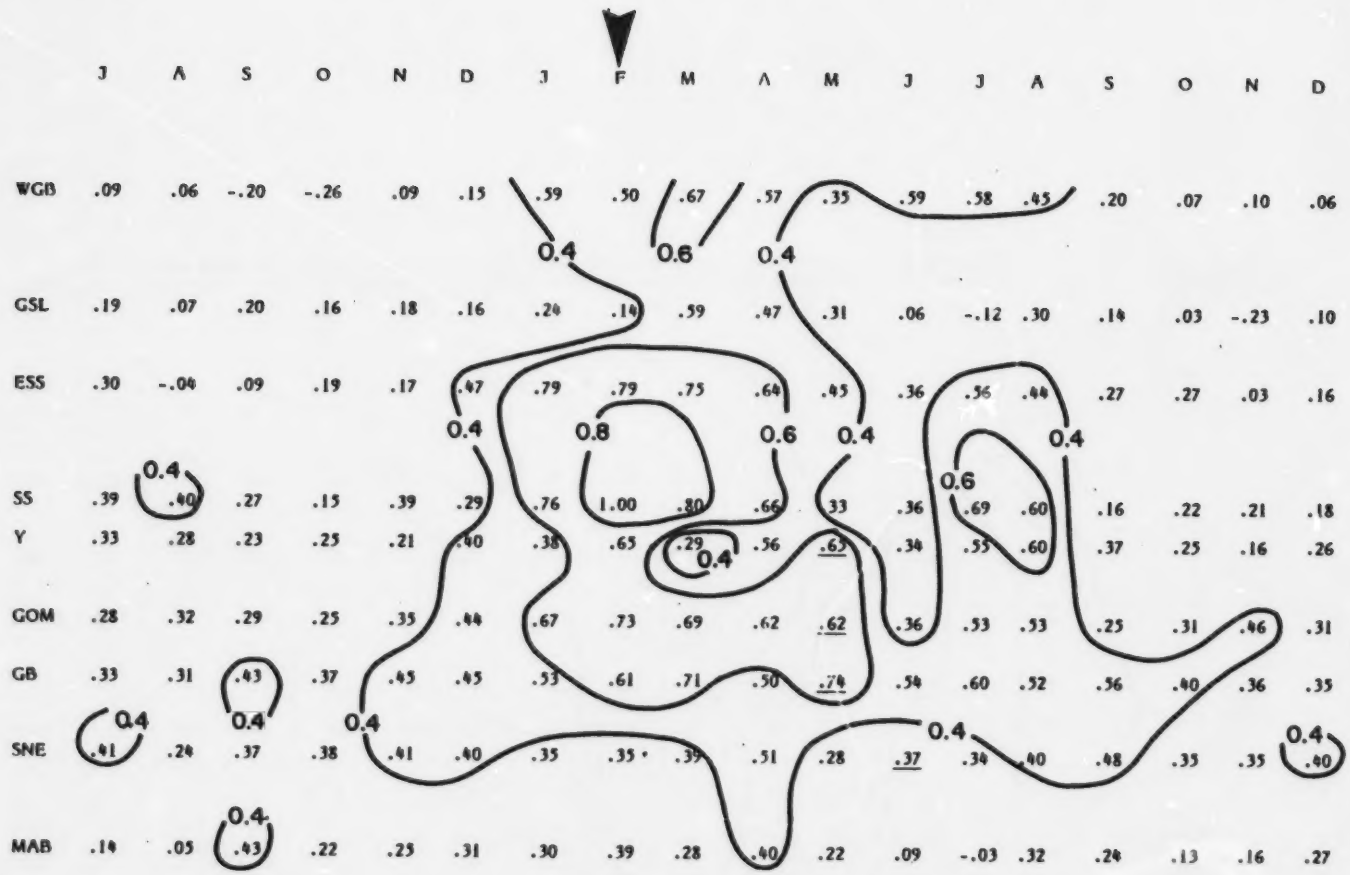

Figure 4c. As in Figure 4a) but for February, 7 equivalent degrees of freedom, $r \geq 0.68$ significant at the 95% level. Underlined entries designate cross-correlation 'peaks' relative to the autocorrelation for the same lag.

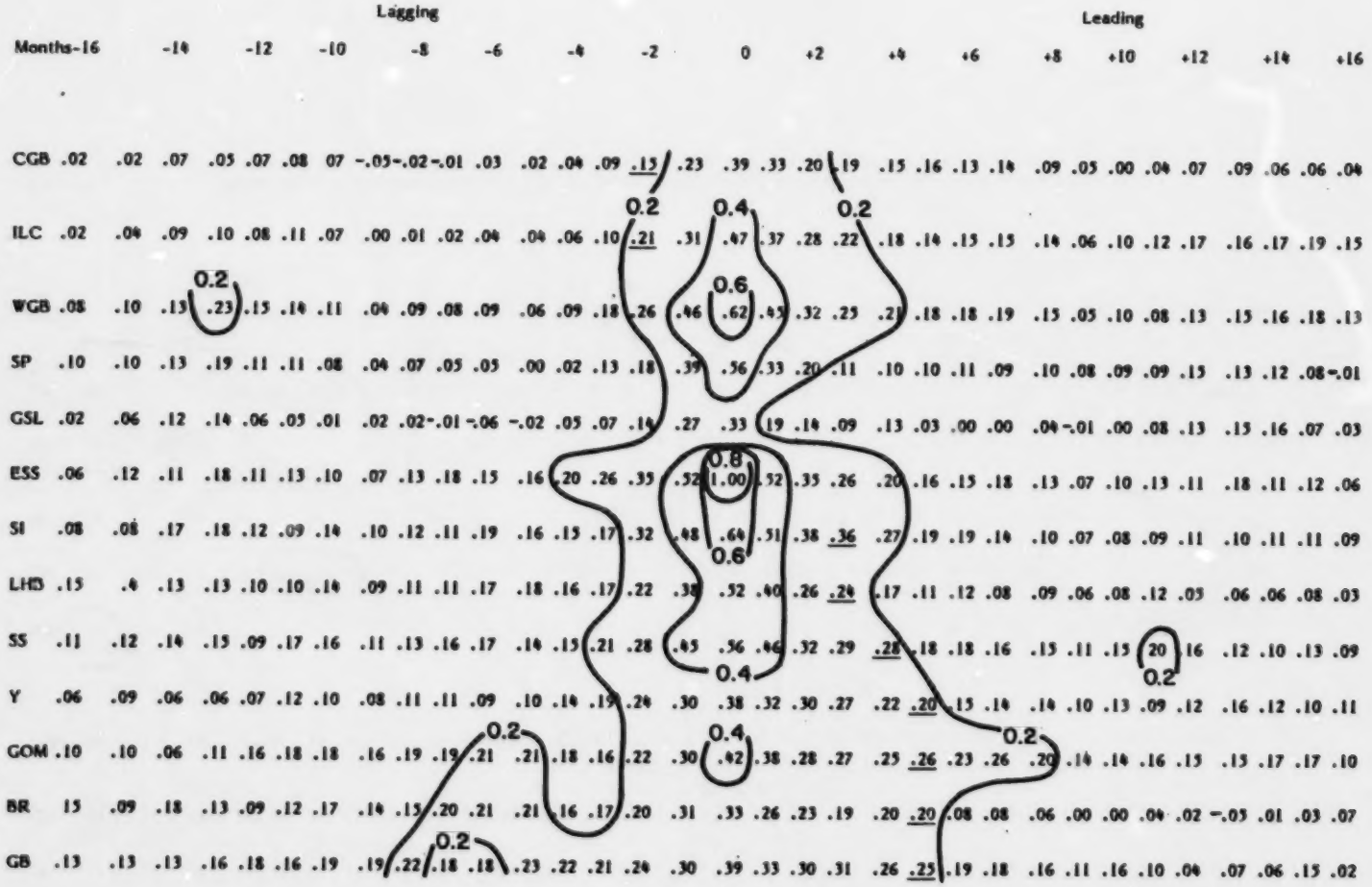

Figure 5. Space-time plot of chronological cross-correlations based on Eastern Shore; 155 equivalent degrees of freedom, r ≥0.13 significant at the 95% level. Underlined entries designate cross-correlation 'peaks' relative to the autocorrelation for the same lag.

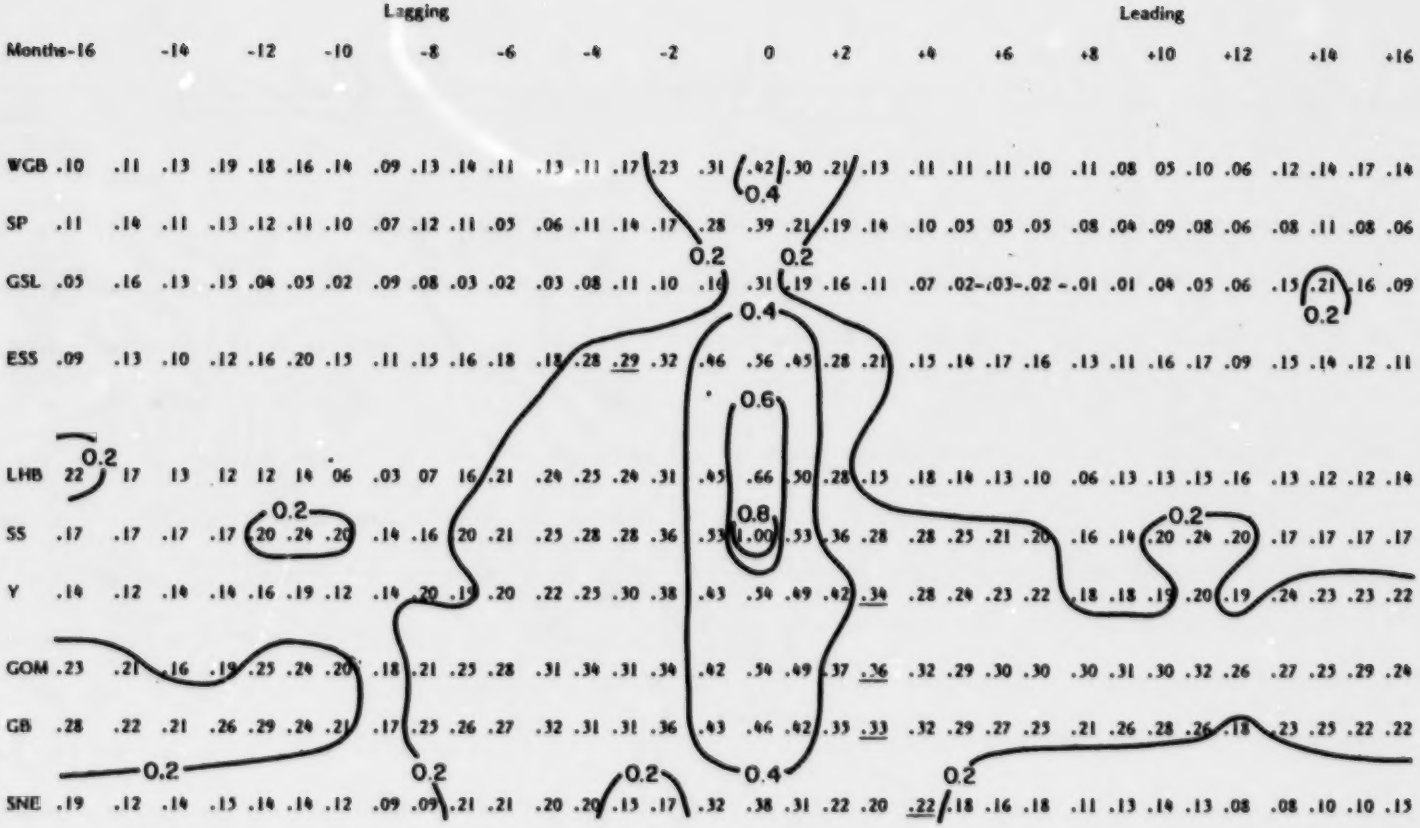

Figure 6. As for Figure 5, but based on South Shore, 124 equivalent degrees of freedom, $r \geq 0.15$ significant at the 95% level. Underlined entries designate cross-correlation 'peaks' relative to the autocorrelation for the same lag.

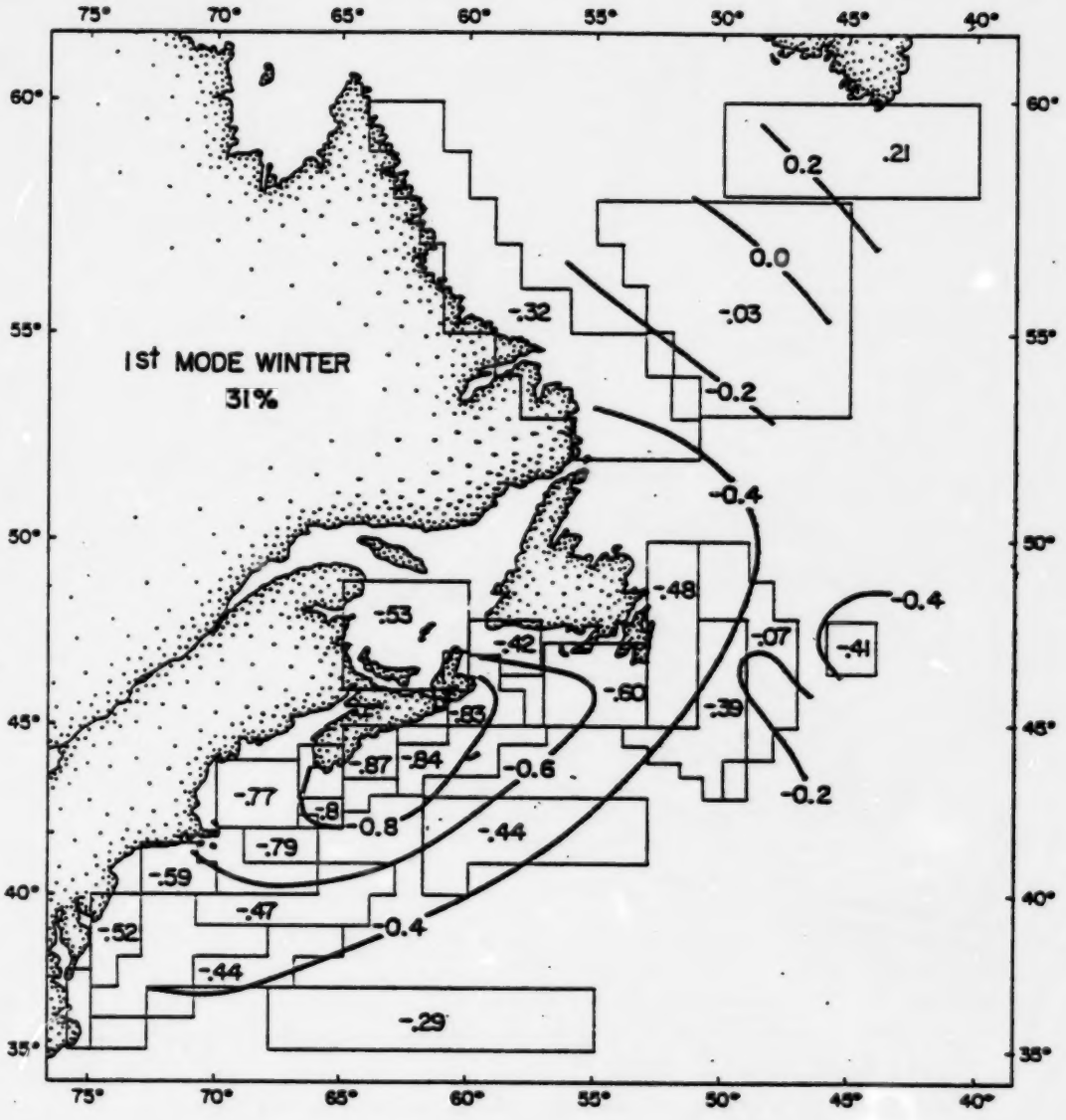

Figure 7a. Charts showing the eigenvector loadings for the first mode EOF's of SST for Winter (Jan-Mar).

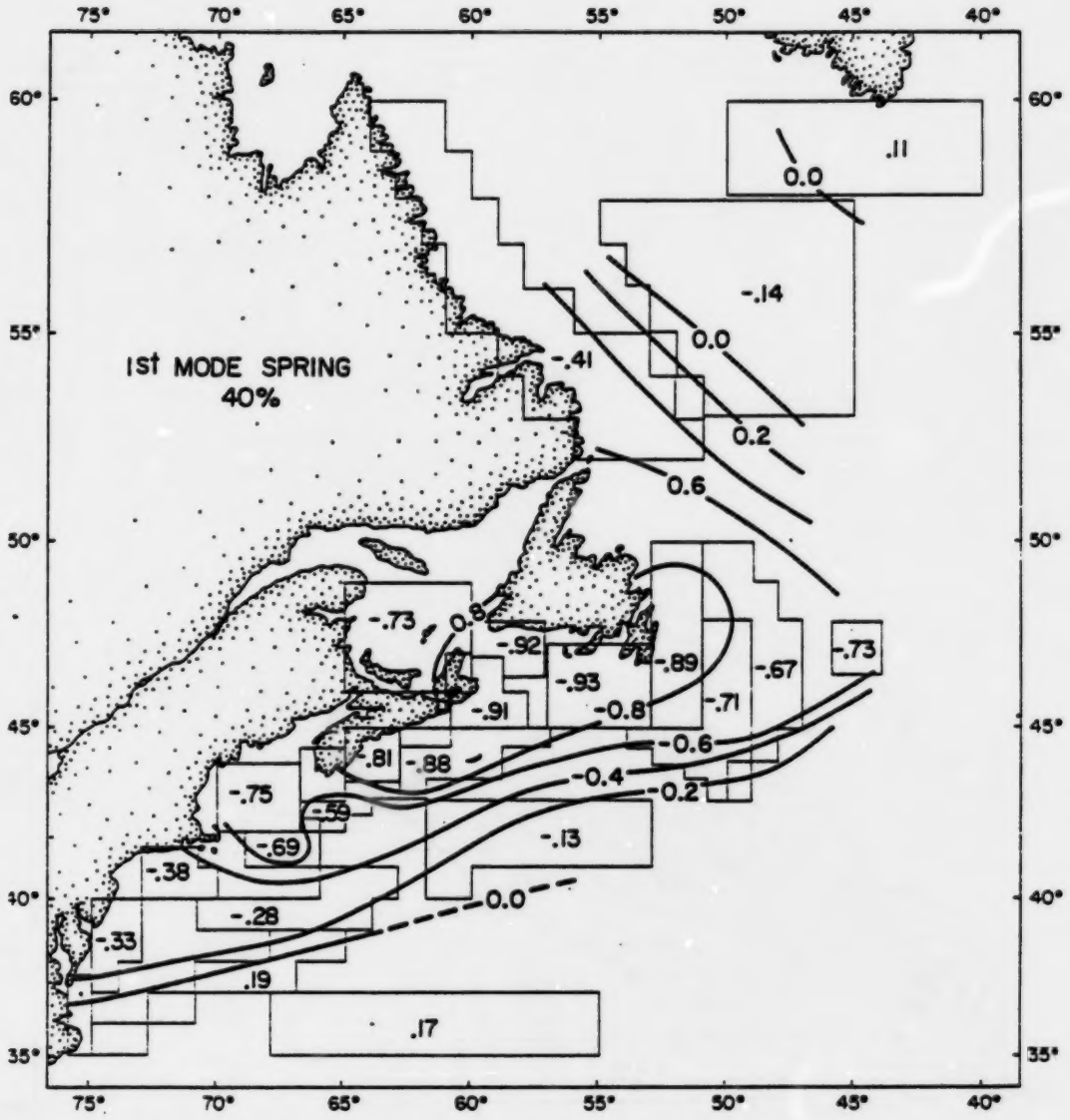

Figure 7b. Charts showing the eigenvector loadings for the first mode EOF's of SST for Spring (Apr-Jun).

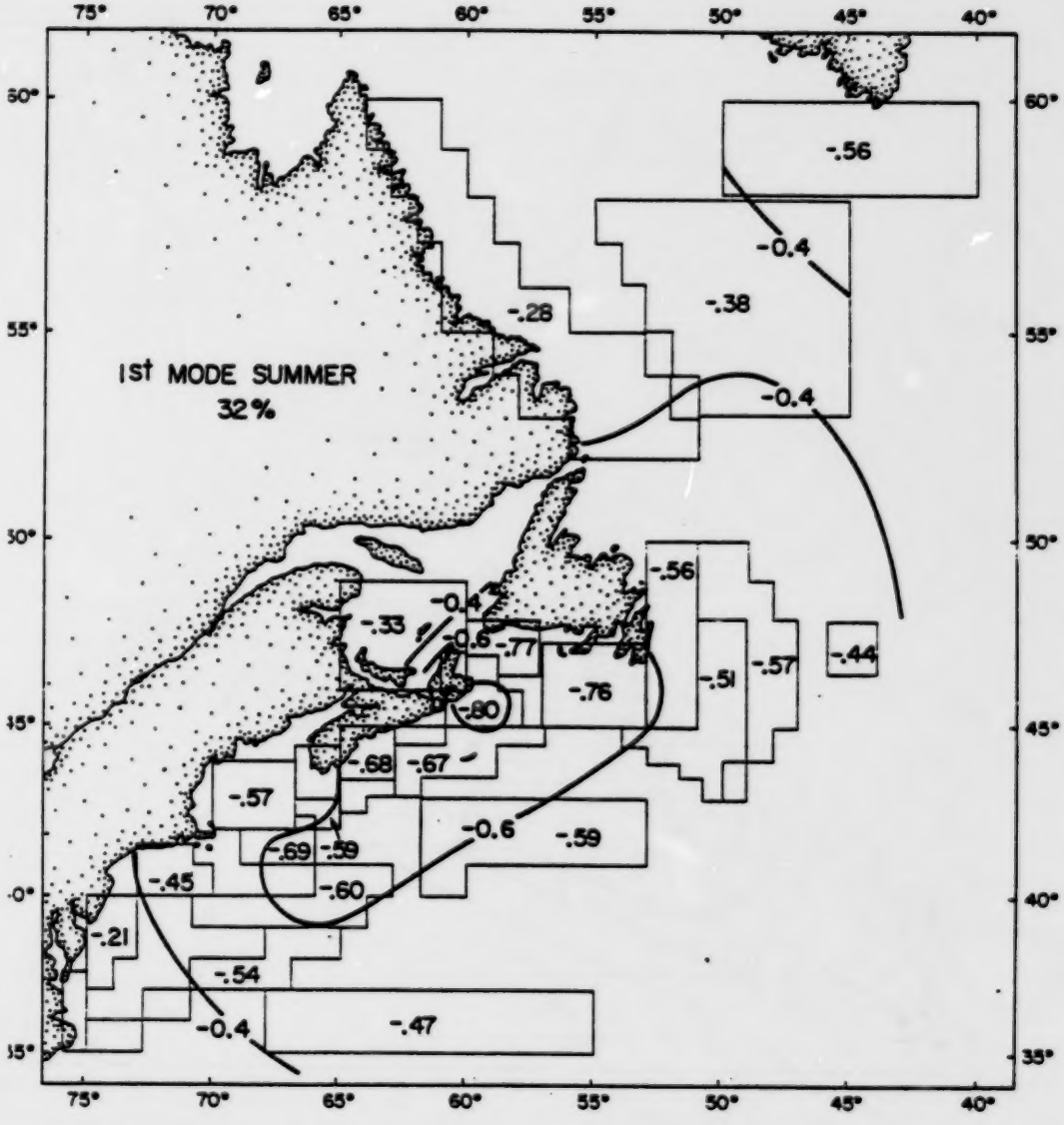

Figure 7c. Charts showing the eigenvector loadings for the first mode EOF's of SST for Summer (Jul-Sep).

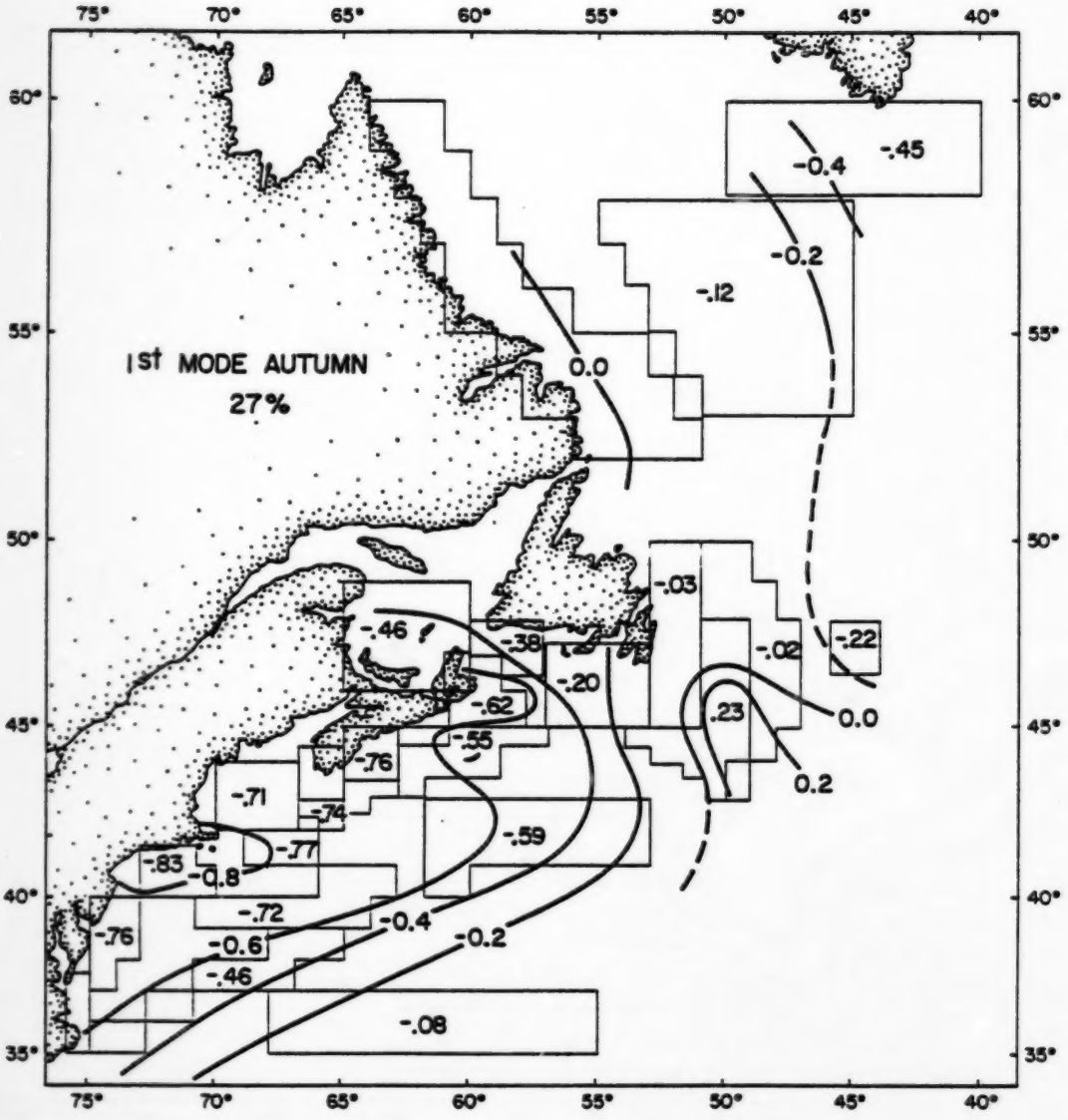

Figure 7d. Charts showing the eigenvector loadings for the first mode EOF's of SST for Autumn (Oct-Dec).

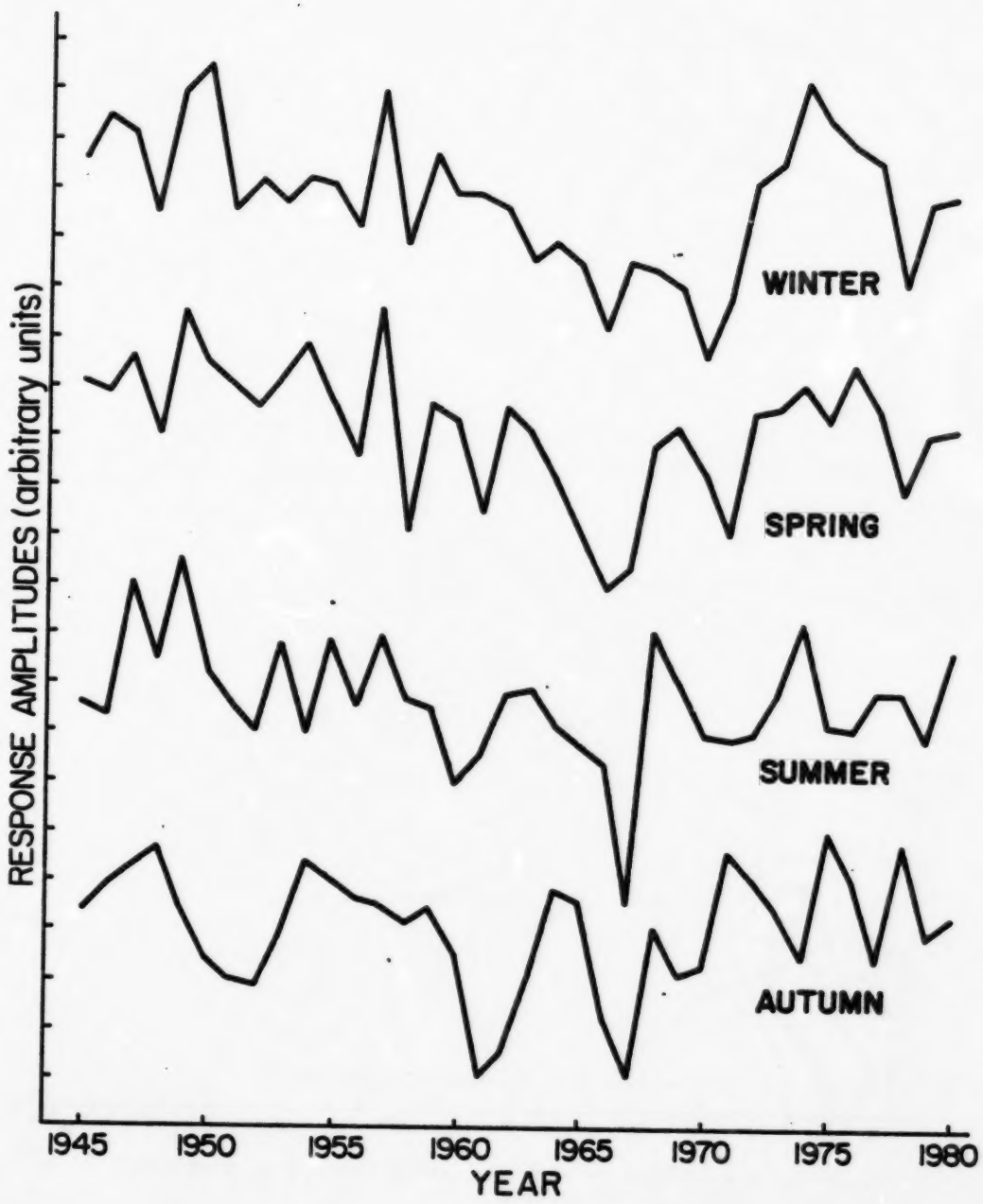

Figure 8 Amplitudes of the first mode EOF's of SST by season. Peaks reflect warm years and troughs, cool years.

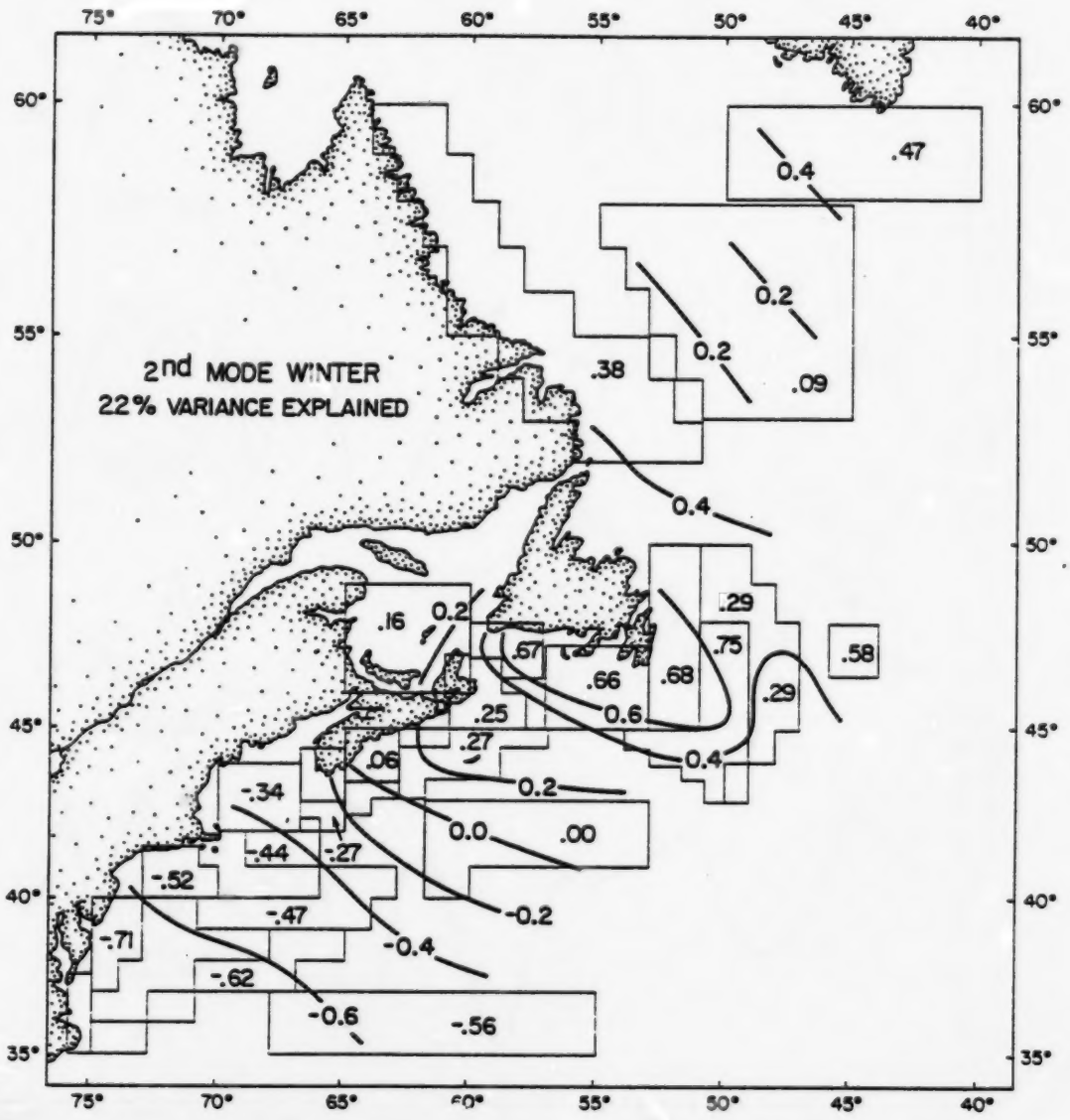

Figure 9a. Charts showing the eigenvector loadings for the second mode EOF's of SST for Winter (Jan-Mar).

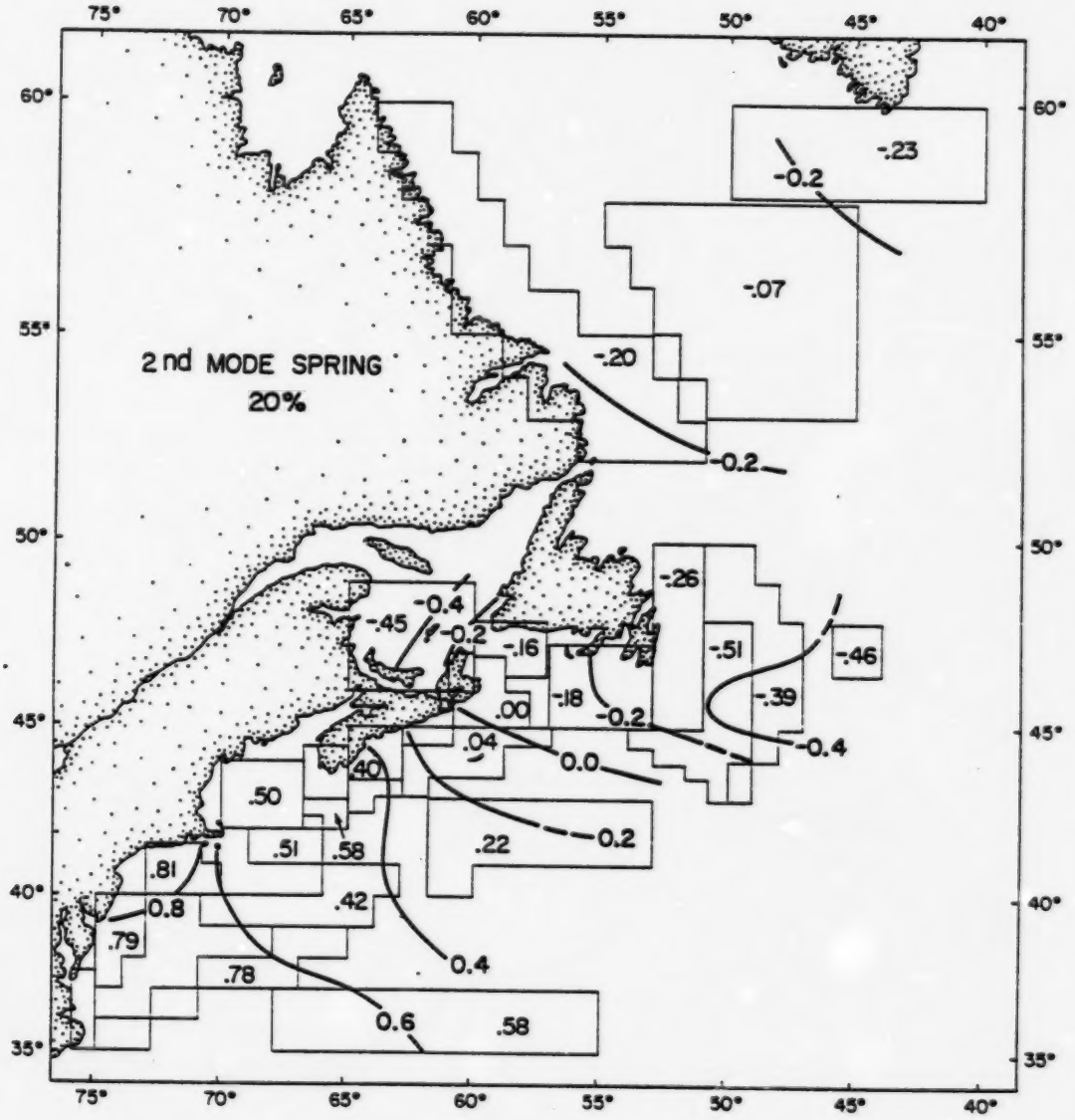

Figure 9b. Charts showing the eigenvector loadings for the second mode EOF's of SST for Spring (Apr-June).

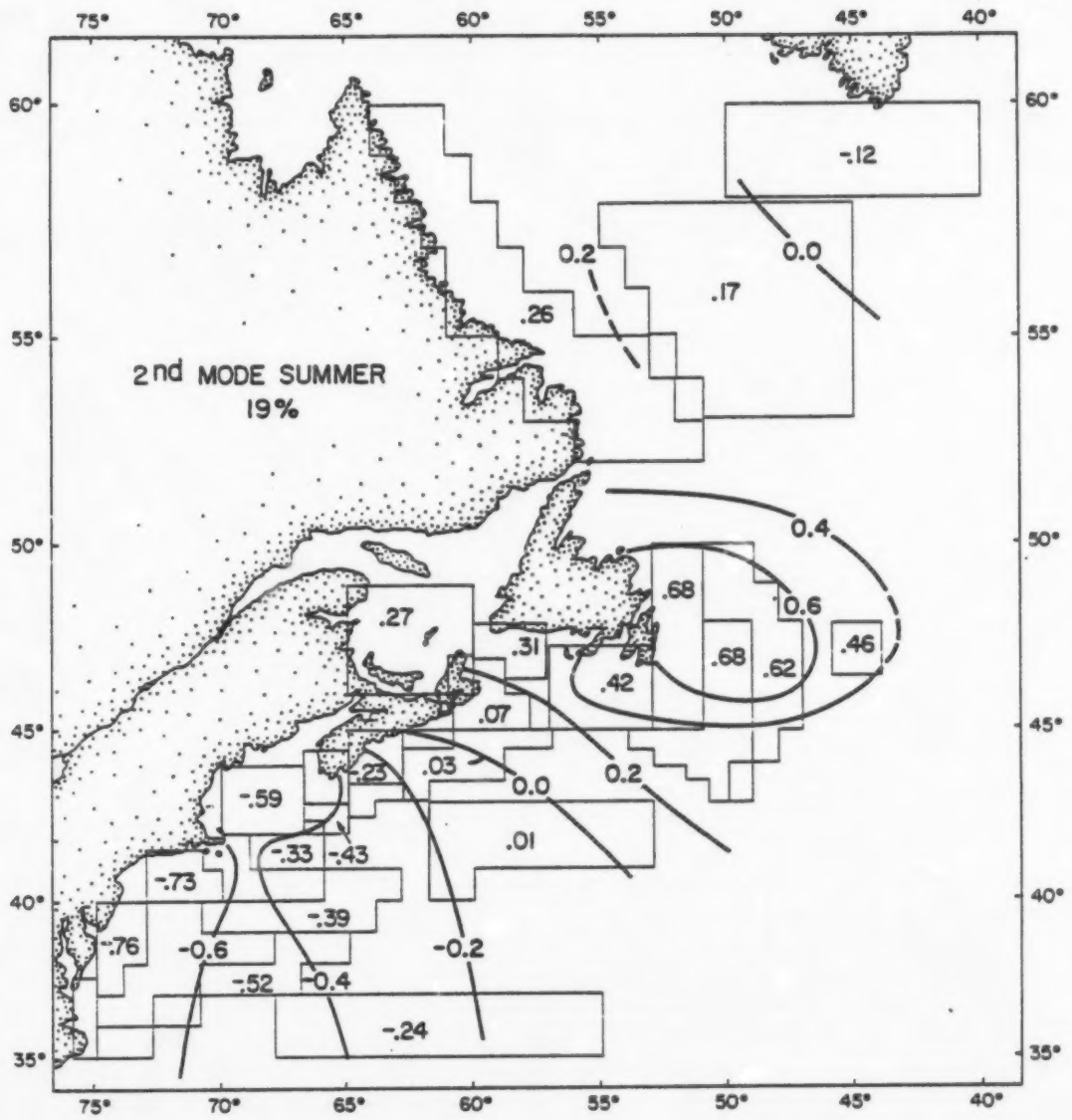

Figure 9c. Charts showing the eigenvector loadings for the second mode EOF's of SST for Summer (Jul-Sep).

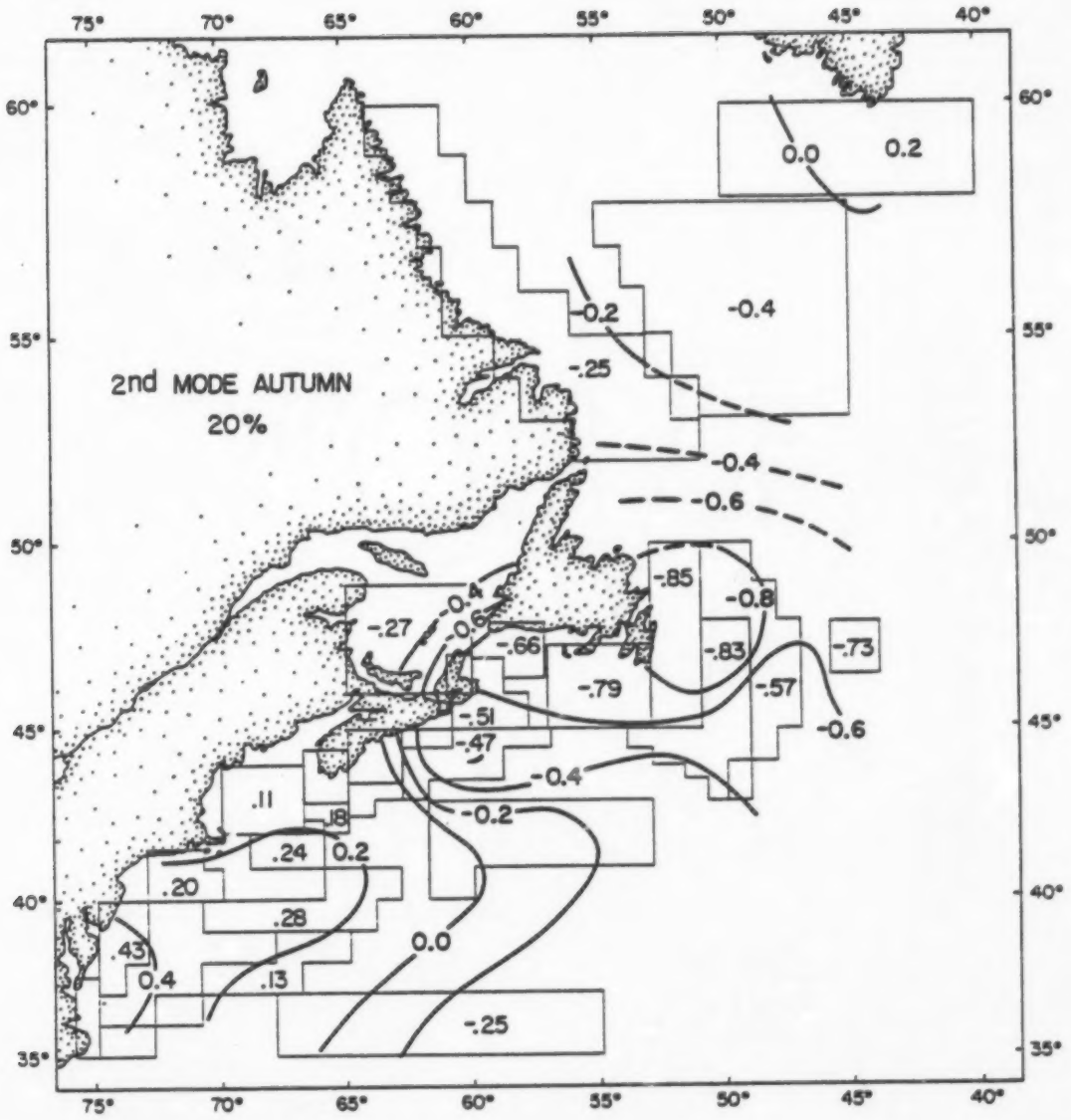

Figure 9d. Charts showing the eigenvector loadings for the second mode EOF's of SST for Autumn (Oct-Dec).

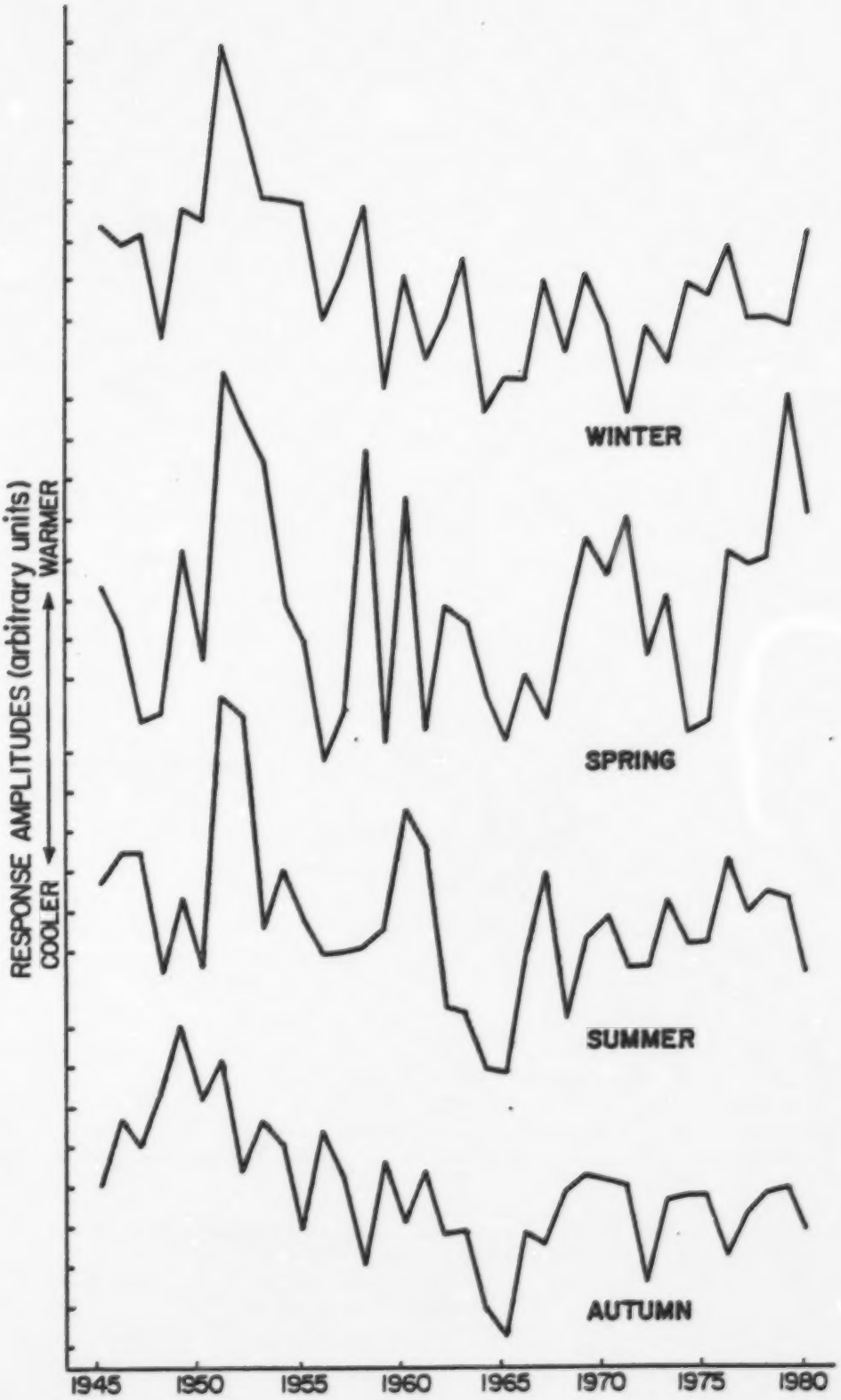

Figure 10. Amplitudes of second mode EOF's by season. Peaks reflect positive anomalies in the New England region and negative anomalies in the Grand Banks region.

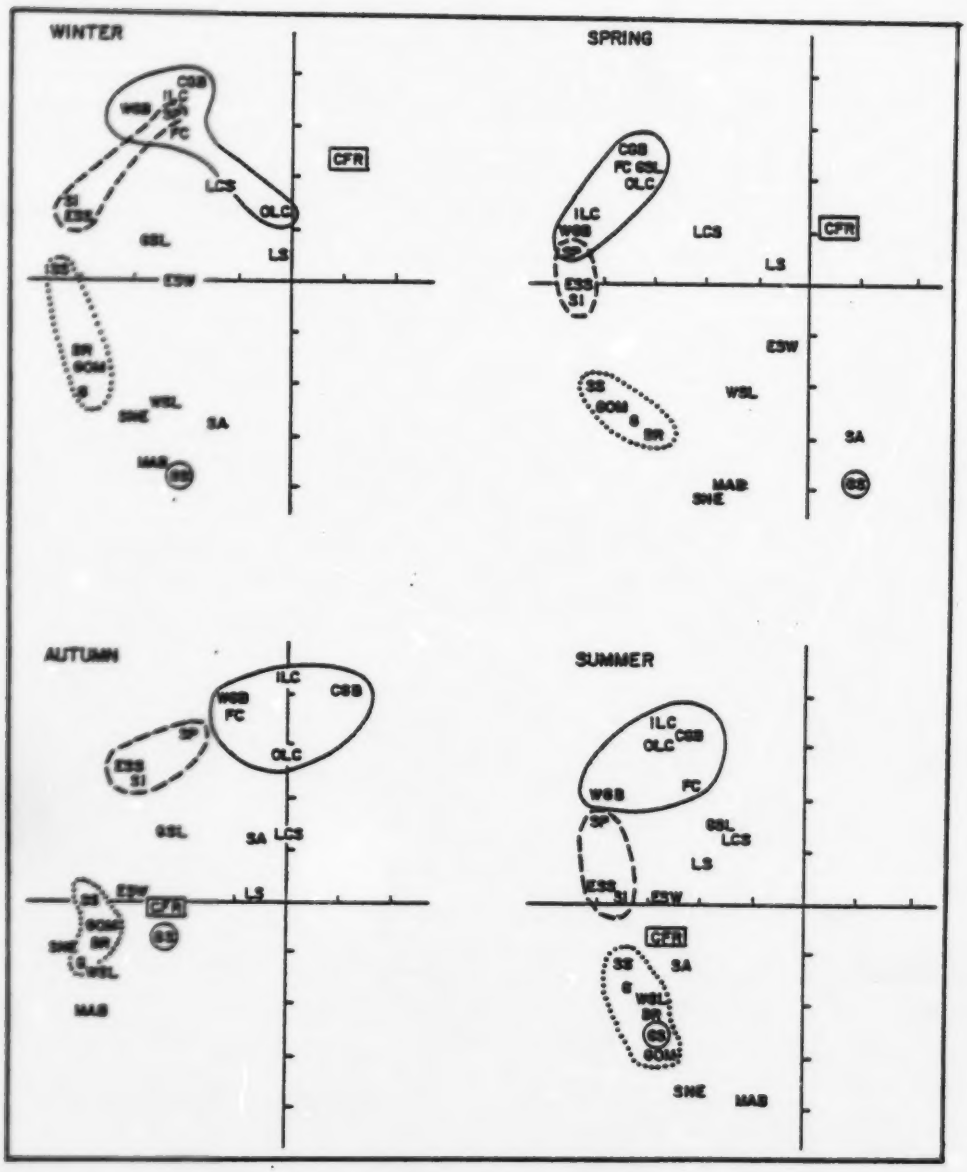

Figure 11. Plot of first vs second mode EOF loadings of SST for all twenty-two ocean areas showing natural groupings.

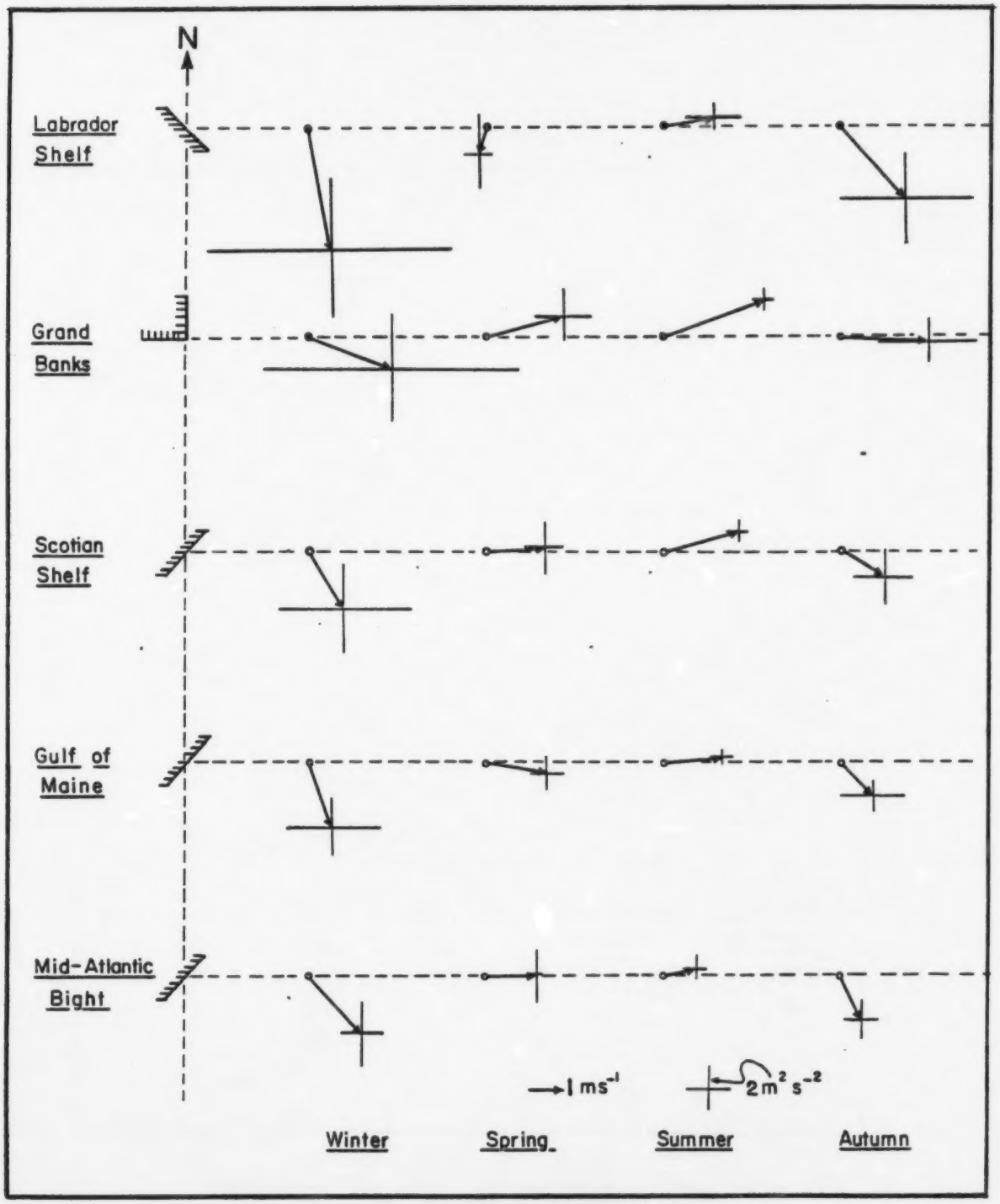

Figure 12. Seasonal average geostrophic wind vectors together with between-year variance components for five locations on the continental shelf (Thompson and Hazen, 1983). The orientation of the adjacent shore is also shown.

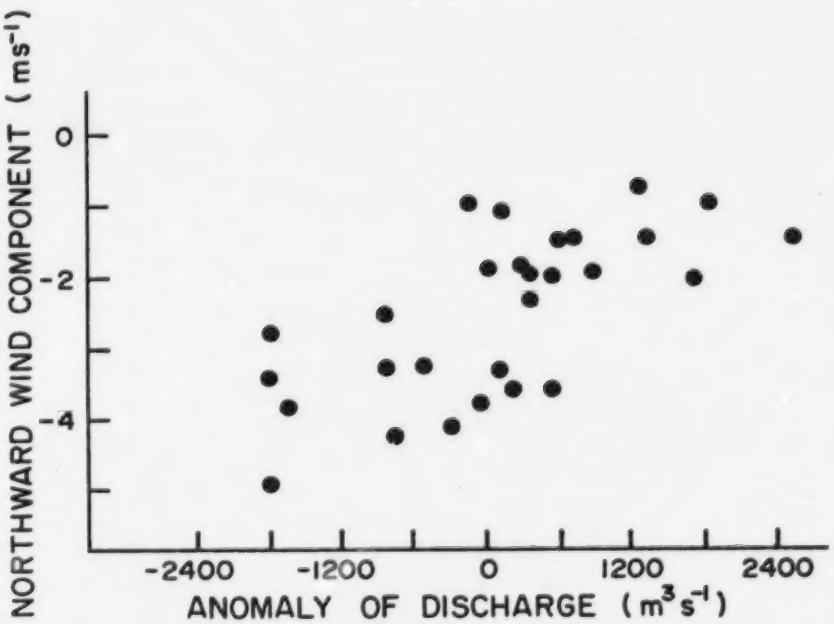

Figure 13. Scatter diagram of the northward component of Scotian Shelf geostrophic winds (in winter) (Thompson and Hazen, 1983) and anomaly of annual discharge of the St. Lawrence Rivers (RIVSUM; Sutcliffe et al., 1976) in that year.

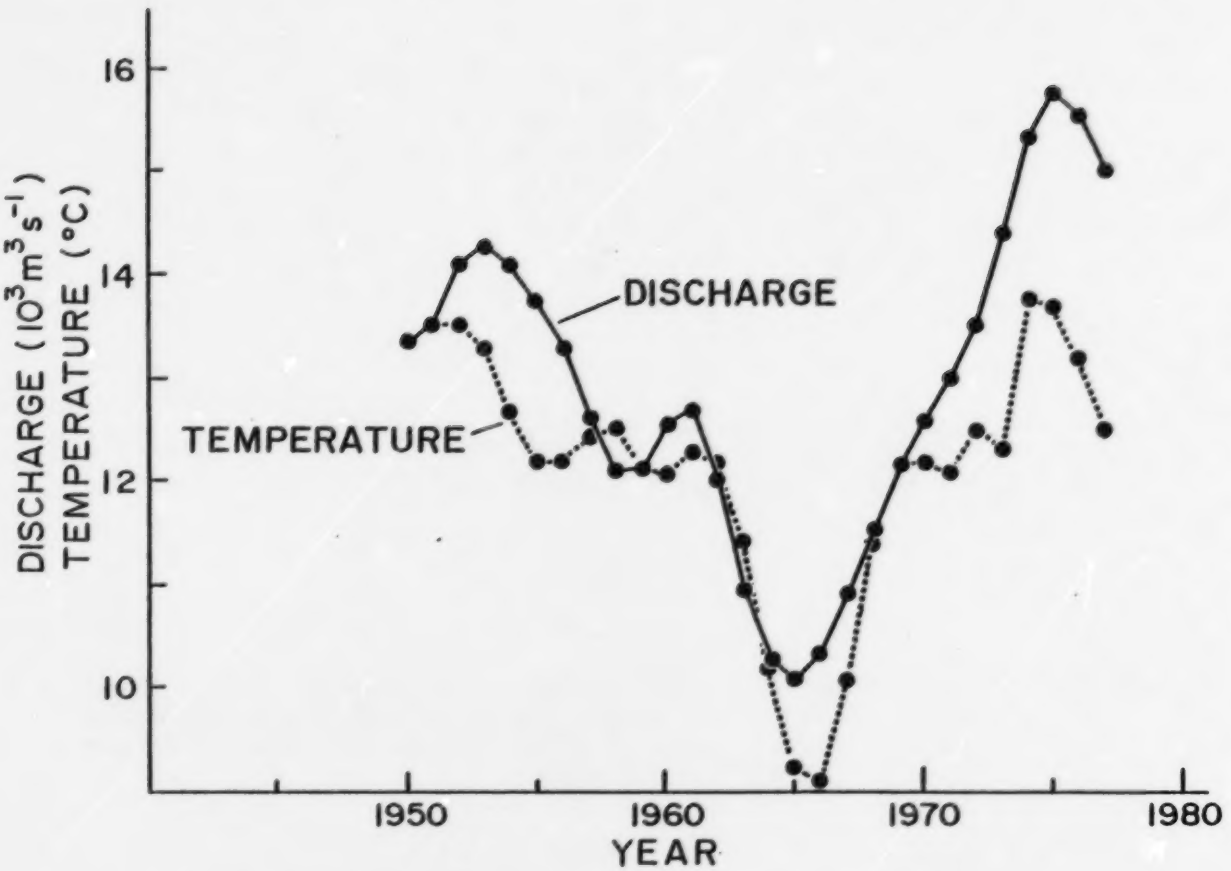

Figure 14. Time plot of spring discharge of St. Lawrence Rivers (averaged over April, May and June and (7-point binomial filter), and the subsequent winter western Slope Water (WSL) surface temperature (averaged over January, February and March and similarly smoothed).

Table 1. Summary of the effect of winds on SST EOF modes

Season	SST Signal	Wind 'Station'	Max SST EOF Variance 'Explained' (%)	Most Effective Wind Direction (°T)
Winter	1st Mode EOF	Midatlantic Bight	5	-
		Gulf of Maine	37	310
		Scotian Shelf	38	310
		Grand Banks	22	310
		Labrador Coast	29	030
	2nd Mode EOF	Midatlantic Bight	10	000
		Gulf of Maine	6	-
		Scotian Shelf	3	-
		Grand Banks	16	130
		Labrador Coast	28	140
Spring	1st Mode EOF	Midatlantic Bight	11	180
		Gulf of Maine	15	310
		Scotian Shelf	35	310
		Grand Banks	52	320
		Labrador Coast	37	010
	2nd Mode EOF	Midatlantic Bight	4	340
		Gulf of Maine	12	000
		Scotian Shelf	7	000
		Grand Banks	4	040
		Labrador Coast	22	340
Summer	1st Mode EOF	Midatlantic Bight	4	190
		Gulf of Maine	16	310
		Scotian Shelf	26	320
		Grand Banks	17	320
		Labrador Coast	3	-
	2nd Mode EOF	Midatlantic Bight	1	-
		Gulf of Maine	0	-
		Scotian Shelf	0	-
		Grand Banks	0	-
		Labrador Coast	3	-
Autumn	1st Mode EOF	Midatlantic Bight	3	290
		Gulf of Maine	16	320
		Scotian Shelf	15	320
		Grand Banks	6	340
		Labrador Coast	14	230
	2nd Mode EOF	Midatlantic Bight	8	090
		Gulf of Maine	7	060
		Scotian Shelf	10	040
		Grand Banks	10	040
		Labrador Coast	1	040

	Gulf Stream	Sargasso Sea	West Slope Water	East Slope Water	Mid-Atlantic Right	South New England	Georges Bank	Gulf of Maine	Browns Bank	LaHave Bank	Tarmouth	South Shore	Sable Island Bank	Eastern Shore	Gulf of St. Lawrence	St. Pierre	West Grand Bank	Central Grand Bank	Offshore Labrador	Inshore Labrador	Labrador Coast	Flemish Cap	Labrador Sea	Cape Farewell
1940	-1.1	-1.7	-2.6	-0.3	-2.6	-2.5	-1.1	-3.2	2.2			-.6	-1.1				-.4	.6	.9			.1		
	-.9	-.1	-.9	-3.9	-1.0	-1.1	-.3	-.3	-.1	-.6	-1.1	-1.6	-1.1	.0		1.3	-1.1	-1.6	.2	-1.8			1.6	2.2
	.2	.2	1.3	1.6	.5	.0	-.3	-.3	1.2	-.6	-1.0	.0	.0	.1	1.1	3.0	-.3	-.0	.5	.3	.8	.5	.2	.2
	.3	.2	1.8	.8	.5	-.4	2.3	-.9	1.9	.3	-.5	-.0	-.3	-1.0	.5	-.9	-.7	-.6	.9	.1		-.3	.9	.8
	.2	.3	.8	1.6	.7	.5	1.9	.1	2.2	.0	.6	.1	-.3	.6		-.9	-.4	.0	1.1	-.3	.0	-.9	.6	-.6
	.6	.4	2.6	-.4	1.0	.0	3.6	.6	-.4	-.4	.2	-.7	-.4	1.0	-1.8	1.2	.1	.5	.4	.5	1.5	1.1	.4	.1
	.8	-.6	.8	1.0	1.5	.8	1.3	.5	-.3	-.6	.2	.5	-.3	.5	-1.1	-.2	.0	-.9	.3	.0	-.2	-.7	.8	.6
	.7	.3	.7	.5	1.7	2.0	.8	1.1	1.1	.5	1.0	-.0	.4	-.1	.0	-.7	-.3	-1.1	-.7	-.6	.6	-.4	.5	.8
	.4	-.4	.7	-.3	1.0	-.1	-.1	-.1	-.3	-.6	-.9	-.8	-.8	-.7	.1	-.9	-1.0	-1.1	-.4	-.6	.5	.3	1.1	1.3
	1.3	.5	1.3	1.0	1.4	2.0	1.8	.8	1.7	1.1	1.6	1.2	.3	.6	1.5	.1	.0	-.5	-.1	-.4	-.6	.1	-.2	-.2
1950	.5	.4	-.3	.7	1.0	.7	.7	1.1	.5	.9	.8	.1	-.3	.0	-.6	-.2	-.3	-.8	-.1	-.4	.4	-.2	-.5	.7
	.3	.3	1.3	2.1	1.0	1.5	1.9	1.5	2.6	1.6	2.5	2.5	2.2	1.7	.7	1.9	1.7	1.6	.6	.9	1.3	1.2	-.1	1.0
	1.0	.3	.7	1.1	.5	1.2	1.2	1.2	1.3	1.6	.8	1.8	1.4	1.5	1.1	1.4	1.8	.9	.5	1.7	.4	1.1	1.4	-.4
	.8	.4	.3	1.8	.5	1.1	.9	1.3	.7	1.1	.8	1.0	.8	.5	.9	-.4	1.3	.8	-.0	1.3	-.6	.2	.5	.1
	1.0	.4	-.3	2.1	.7	1.1	.9	.7	.1	.5	.1	.5	.7	.3	-.6	-.2	-.3	.0	-.6	-.4	.6	.2	1.0	.9
	.7	.0	-.1	1.2	.3	1.1	-.2	.5	.5	.7	-.1	.6	.0	-.3	-.0	.2	-1.1	-.3	-.2	-.5	.0	.1	.8	-.0
	.3	.1	-.3	1.1	-.7	-.1	-.5	-.4	-.3	-.1	-.6	-.3	-.3	-.6	-.6	.8	-.3	-.2	.7	-.2	-.0	-.0	-.2	-.5
	.8	.4	.7	.4	.7	1.1	.3	.5	.2	-.2	-.4	-.5	.0	-.3	-1.5	-.6	-1.1	-1.1	-1.8	-.6	-.6	-.5	-.0	.0
	-.8	.5	-.3	.5	-.4	-.2	.1	-.0	-.1	.9	.3	.8	.7	1.1	.0	.1	.6	.6	.0	.5	.4	.8	-.6	1.8
1960	1.0	.4	-1.4	1.0	.1	.2	-.7	-.4	-.3	-.0	-.3	-.5	-.6	-.4	-.2	-.3	-.6	-.3	-1.1	-.6	-.4	-.4	-.3	.2
	.6	.4	-.6	.5	.5	.2	.1	.0	-.2	1.0	-.3	.3	.9	.6	.0	.3	.0	.6	2.9	.4	-.5	.4	-.1	.3
	-.3	.5	.2	-.1	-.8	-.2	-.9	-.7	-.8	-.6	-1.2	-.7	.0	-.0	.2	.0	.1	-.0	2.5	1.1	.2	.7	-.1	.8
	-.3	.3	-.3	-.6	-.0	.2	-.8	-.4	-.0	-.0	-.6	-.0	-.3	-.3	-.0	.8	.2	.1	.5	.3	.4	.7	-.1	.6
	-.2	-.2	.4	-.1	-.6	-.2	-.4	-.0	.3	-.0	-.5	-.1	-.6	-.3	-.2	.1	.0	.4	.4	.6	.4	.2	.0	.8
	-.3	-.6	-1.4	-.2	-1.1	-.6	-1.3	-1.4	-1.4	-.9	-1.2	-1.4	-.7	-.8	-.2	-.6	-.7	-.4	-.9	-.7	-.6	.0	.0	.1
	-.2	-.1	-1.1	-.2	-.9	-1.3	-1.3	-1.9	-1.3	-1.1	-2.1	-1.7	-.8	-1.0	-.1	-.8	-.3	-.1	-.3	-.0	-.2	.2	.6	.1
	-.3	-.1	-2.3	-1.2	-1.1	-.8	-1.0	-1.3	-.3	-.3	-1.4	-.8	-.2	-.0	.1	-.1	.0	.7	1.0	.4	.4	1.2	.9	.3
	-.3	-.0	-1.2	-.3	-1.1	-1.3	-1.3	-1.3	-.7	-.1	-1.8	-.3	.6	-.1	-.2	.7	1.1	2.6	.2	1.6	.7	1.0	.8	-.3
	-.3	-.2	.2	-.7	-.4	-.1	-1.3	-.9	-.2	.4	-.4	.1	.3	.2	.3	.0	.0	.0	-.1	-.3	-.6	-.2	-.3	-2.7
1970	-.6	-.3	-.3	-.3	-.4	-.2	.3	.3	.3	1.1	.2	.8	.7	.3	.4	.3	.4	.6	.7	.4	.2	-.1	-.4	-1.5
	-.7	-.6	-.3	-.6	-1.1	-.6	-.2	.1	-.1	.3	.3	.2	.7	.3	.7	.9	.6	1.2	.3	.6	.3	.8	-.9	-.9
	-.8	-.6	-1.3	-.2	-.1	-1.9	-.7	-.1	-.6	-.3	-.4	-.4	-.1	-.1	.4	-.0	.0	.4	-.2	.1	.3	-.3	-.9	-.6
	-.4	-.3	-.3	.1	-.6	-1.2	-.4	-.1	-.4	-.1	.3	.3	.1	-.7	-.9	-.6	-.1	-.6	-.3	-.3	-.8	-.3	-1.4	-1.0
	-.2	-.2	-.2	-.1	.3	-.0	.3	.2	.1	.4	.8	-.1	-.3	-.3	.3	-.3	-.1	-.3	-.2	.0	-.0	-.4	-.2	-.9
	.1	-.2	.3	-.4	.0	.3	.3	.3	.8	.3	.8	-.1	-.1	-.3	-.4	-1.2	-.3	-.8	-.7	-.9	-1.4	-1.6	-.3	-.4
	.1	.1	.3	.2	.1	.3	-.1	-.2	-.3	-.3	-.1	-.1	-.3	-1.0	-.6	-.8	-.6	-.3	-.4	-.8	-.2	-.6	.3	-.7
	-.3	-.2	.3	.3	-.3	.1	.9	.3	1.1	1.1	1.0	1.0	.3	.2	.2	.0	.4	-.0	-.3	-.0	-1.2	-.6	-.3	-1.4
	-.1	-.2	.1	.4	-.1	-.2	.3	.3	.2	-.1	.2	.2	.3	.0	-.1	.2	-.0	.3	-.2	-.2	-.8	-.2	.1	-.2
	-.6	-.3	-1.3	-.8	-.6	-.4	-.8	.1	.2	.8	.3	.7	.6	.3	.5	.0	.6	.3	.1	.3	.1	-.3	-.2	-.3
1980	-.3	.0	.8	-2.1	.0	.2	.6	.7	.0	.8	.8	.4	.4	.3	.9	.2	.1	.4	.9	.7	-.2	1.0	.2	-.3
	-.2	-.2	.2	-.6	-.0	.4	.1	-.1	-.0	.4	.3	.3	-.0	.0	1.0	-.1	.0	.1	-.9	.4	.1	-.4	.3	-.6
	23.0	21.9	17.7	15.9	16.4	11.6	9.8	8.9	8.3	7.9	7.4	7.3	7.2	5.8	5.0	5.2	4.9	5.0	4.3	3.9	2.2	6.6	5.2	5.1
GRAND MEDIAN																								
	2.4	2.2	5.0	6.4	4.3	4.3	5.1	4.7	3.9	2.7	4.3	4.2	3.3	2.7	3.3	4.2	2.9	4.2	4.7	3.3	2.9	2.8	3.0	4.9
RANGE																								

APPENDIX A Table of annual sea surface temperature anomalies (°C) from the grand median over the period 1940-1980 for 24 grouped areas in the Northwest Atlantic